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# FEASIBILITY OF EMISSION STANDARDS BASED ON PARTICLE SIZE

MIDWEST RESEARCH INSTITUTE

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# FEASIBILITY OF EMISSION STANDARDS BASED ON PARTICLE SIZE

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Program Element 1HA091

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# ABSTRACT

The technical and economic feasibility of particulate emission standards based on particle size was assessed in this program. Specific attention was focused on standards to regulate the emission of fine particulates--particulates below 2 μ in size.

The program was divided into four major areas of effort:

1. Analysis of approaches for regulating fine particle emissions from stationary sources.

2. Definition of technological and economic requirements necessary for implementation of emission standards.

3. Identification of benefits that would accrue if control procedures for fine particulates can be implemented.

4. Assessment of overall feasibility of implementation of fine particle emission standards.

The analysis of the implications of emission standards based on particle size identified some deficiencies in control technology that will limit the type of standards that can be proposed and implemented in the near future. The economic impact of fine particulate control was found to vary substantially from industry to industry. Estimates of costs associated with the control of fine particulates varied from less than 1.0% up to 20% of the value of the product.

The lack of data on the damages associated with fine particulate pollution hampered efforts at meaningful cost/benefit analysis. The limited cost/benefit analysis performed indicated that the optimum control efficiency for fine particulates varied with population density.

In general, emission standards based on particle size were judged to be both technically and economically feasible. The most realistic approach would be to tailor the emission standard to specific sources of fine

particulate pollutants. Tailoring of standards permits a greater degree of flexibility in an overall control plan for fine particulates, and acknowledges the differences in the importance and difficulty of control of individual sources.

## CONTENTS

Abstract ii

List of Figures vii

List of Tables ix

Acknowledgments xiii

Sections

I Summary 1

- Goal(s) for Program to Control Fine Particulates 1
- Approaches for Regulation of Fine Particulate Emissions 2
- Technical Implications of Emission Standards 3
- Economic Impact of Emission Standards 5
- Benefit/Cost Relationships for Fine Particulate Control 5
- Overall Feasibility of Emission Standards Based on Particulate Size 9

II Recommendations for Future Work 11

- Introduction 11
- Source Sampling and Monitoring Methods 11
- Fine Particle Emission Rates 11
- Control Technology Evaluation 12
- Control Technology Development 12
- Analysis of Relationships Between Source Emissions and Ambient Air Quality 12
- Economic Impact Analysis 13
- Cost/Benefit Analysis 13

III Introduction 14

IV Role of Fine Particles in Air Pollution 16

- Introduction 16
- Effects of Fine Particulates on Human Health 20
  - Deposition, Retention, and Clearance Processes in the Respiratory System 21
  - Clearance of Particulate Matter from the Respiratory System 24
  - Toxicological Studies of Atmospheric Particulate Matter 24
  - Epidemiological Studies of Atmospheric Particulate Matter 26
- Modification of Properties of the Atmosphere 27
  - Visibility 29
  - Solar Radiation 33
  - Weather Modification 34

CONTENTS (Continued)

Page

V Sources of Fine Particulate Emissions 36

Nature of the Particulate Pollution Problem 36
Principal Sources of Fine Particulates 40
Summary of Fine Particle Emissions 41
Priority List for Sources of Fine Particle Emissions 46

VI Approaches for Regulating Fine Particle Emissions 53

Introduction 53
Methods for Regulating Fine Particle Emissions 56
Basis for Emission Standards for Fine Particulates 58
Plume Opacity Standards 60
Minimum Collection Efficiency for Fine Particulates 62
Mass-Emission Regulations 63
Emission Standards Selected for Evaluation 66

VII Technological Implications of Fine Particle Emissions Regulations 68

Introduction 68
Requirements for Control Equipment Efficiency 68
Capability of Control Technology 71
Capability of Existing Control Equipment 71
Emerging and New Control Technology 74
Summary of Status of Control Technology 77
Requirements for Compliance Testing and Monitoring 78
Compliance Monitoring Methods for Plume Opacity 82
Compliance Monitoring Methods for Mass Emissions 85
Summary of Recommended Compliance Monitoring Methods 92

VIII Economic Impact of Fine Particle Emission Standards 93

Introduction 93
Determination of Cost vs Efficiency Relationships for Control Devices 94
Methodology for Determining Costs Required for Compliance with Fine Particle Emission Standards 98
Development of Model Plants for Important Industrial Sources of Fine Particle Emissions 98
Determination of Control Device Performance Requirements 99
Costs to Model Plant and Industry for Compliance with Specific Fine Particle Emission Standards 101
Estimated Reductions in Fine Particle Emissions 130
Economic Impact of Fine Particle Emission Standards on Selected Sources 133
Example of Calculation of Economic Impact 135
Control Costs in Selected Industries 138

CONTENTS (Continued)

Page

IX Benefit/Cost Relationships for Fine Particulate Control 147

Introduction 147
Determination of Economic Damage Attributable to a Specific Source 147
Computing the Impact Area 149
Control Costs 151
Economic Damage 151
Total Economic Damages 153
Cost/Benefit Relationships 157

X Overall Feasibility of Emission Standards Based on Particulate Size 166

Introduction 166
Feasibility of Specific Types of Standards 166
Opacity Regulations 167
Regulation Based on Best Installed Control System 168
Mass Emission Regulations 168

XI References 170

XII Glossary of Terms 178

XIII Appendices 180

Appendix A - Control Technology for Fine Particles 180
Appendix B - Example of Procedure for Determining Control 207
Costs for Compliance with Fine Particle 207
Emission Standards
Appendix C - Plume Opacity 213

L

# FIGURES

No. Page

1 Relationship between particle mean residence time and particle size . . . . . . . . . . . . . . . . . . . . . 18

2 Effects of particulate air pollution in the community as related to particle size. . . . . . . . . . . . . . . . . 19

3 Fraction of particles deposited in the three respiratory tract compartments as a function of particle diameter . . 23

4 Effect of irritants in major bronchi. . . . . . . . . . . . 28

5 Effect of irritants in terminal bronchioles . . . . . . . . 28

6 Effect of irritants in alveoli. . . . . . . . . . . . . . . 18

7 Meteorological visibility vs particle size, ferric sulfate aerosol . . . . . . . . . . . . . . . . . . . . . . 31

8 Meteorological visibility vs particle size, flyash aerosol . . . . . . . . . . . . . . . . . . . . . . . . . 32

9 Plume opacity as a function of particle diameter and dust loading . . . . . . . . . . . . . . . . . . . . . . . . 61

10 Representative emission standards based on potential emission rate . . . . . . . . . . . . . . . . . . . . . . . 65

11 Extrapolated fractional efficiency of control devices . . . 73

12 Forces operating on aerosol particles . . . . . . . . . . . 76

13 Recommended manual method for monitoring compliance of sources with fine particle emission regulations . . . . . 87

FIGURES (Concluded)

No. Page

14 Semicontinuous method for monitoring fine particle emissions . . . . . . . . . . . . . . . . . . . . . . . . . 88

15 Schematic diagram of monitoring system utilizing quartz crystal microbalance. . . . . . . . . . . . . . . . . . . . . 90

16 Annualized cost for operation of high-voltage electrostatic precipitators. . . . . . . . . . . . . . . . . . . . . . . 95

17 Installed costs for control equipment . . . . . . . . . . . 96

18 Annualized costs for control equipment. . . . . . . . . . . 97

19 Interrelationships among factors affecting the economics of a firm . . . . . . . . . . . . . . . . . . . . . . . . .134

20 Structure for microeconomic impact analysis . . . . . . . .136

21 Simplified hemispherical pollutant dispersion model . . . .150

22 Economic damage resulting from continuous exposure to 75 $\mu g/m^3$ fine particulate concentration . . . . . . . . .156

23 Fine particulate control costs for 400-MW coal-fired electric generating plant . . . . . . . . . . . . . . . .159

24 Total annual economic costs of fine particulate control at various population densities . . . . . . . . . . . . .164

25 Optimum fine particle control level at various population densities . . . . . . . . . . . . . . . . . . . . . . . . .165

# TABLES

No. Page

1 Estimates of Fine Particle Emissions as a Function of Emission Standard . . . . . . . . . . . . . . . . . . . . 4

2 Effect of Control Criteria on Control Costs in Selected Industries . . . . . . . . . . . . . . . . . . . . 6

3 Total Annual Cost of Achieving BICD-Level Control of Fine Particulates in Selected Industries. . . . . . . . 7

4 Summary of Fine Particulate Control Costs at BICD-Level Control . . . . . . . . . . . . . . . . . . . . 8

5 Classification of Particulate Pollutants. . . . . . . . . 17

6 Major Industrial Sources of Particulate Pollution . . . . 37

7 Nonindustrial Sources of Particulate Pollution. . . . . . 38

8 All Major Sources of Particulate Pollution. . . . . . . . 39

9 Fine Particle Emissions from Industrial Sources . . . . . 42

10 Fine Particle Emissions from Mobile Sources . . . . . . . 45

11 Profile of the Characteristics of Particulate Pollutants Emitted by Various Industrial Sources . . . . . . . . . 47

12 Priority List for Sources of Fine Particle Emissions. . . 52

13 Estimated Concentrations of Los Angeles Aerosol Particles by Source . . . . . . . . . . . . . . . . . . . 55

TABLES (Continued)

No. Page

14 Control Device Efficiency Required to Achieve Various Plume Opacity Levels . . . . . . . . . . . . . . . . . . . 70

15 Measurement and Monitoring Methods for Fine Particulates. . . . . . . . . . . . . . . . . . . . . . . . . 79

16 Control Equipment Costs for Coal-Fired Electric Utility Plants . . . . . . . . . . . . . . . . . . . . . . . 102

17 Incremental Annualized Costs for Coal-Fired Electric Utility Plants to Meet Fine Particle Emission Standards . . . . . . . . . . . . . . . . . . . . . . . . 103

18 Control Equipment Costs for Sinter Machine (Windbox) . . . 105

19 Incremental Annualized Costs for Sinter Machines (Iron and Steel) to Meet Fine Particle Emission Standards. . . 106

20 Control Equipment Costs for Basic Oxygen Furnaces (Iron and Steel Plants). . . . . . . . . . . . . . . . . . . . 107

21 Incremental Annualized Costs for Basic Oxygen Furnaces to Meet Fine Particle Emission Standards . . . . . . . . 108

22 Control Equipment Costs for Electric Arc Furnaces (Iron and Steel Plants). . . . . . . . . . . . . . . . . . . . 110

23 Incremental Annualized Costs for Electric Arc Furnaces to Meet Fine Particle Emission Standards . . . . . . . . 111

24 Control Equipment Costs for Cement Plant Rotary Kilns. . . 112

25 Incremental Annualized Costs for Cement Kilns to Meet Fine Particle Emission Standards . . . . . . . . . . . . 113

26 Control Equipment Costs for Hot-Mix Asphalt Plant Rotary Dryers . . . . . . . . . . . . . . . . . . . . . . . 115

27 Incremental Annualized Costs for Hot-Mix Asphalt Plant Rotary Dryers to Meet Fine Particle Emission Standards . . . . . . . . . . . . . . . . . . . . . . . . 116

TABLES (Continued)

No. Page

28 Control Equipment Costs for Ferroalloy Furnaces (Closed Electric Furnace). . . . . . . . . . . . . . . . . 117

29 Control Equipment Costs for Ferroalloy Furnaces (Hooded Open Electric Furnace) . . . . . . . . . . . . . 118

30 Control Equipment Costs for Ferroalloy Furnaces (Unhooded Open Furnace). . . . . . . . . . . . . . . . . 119

31 Control Equipment Costs for Rotary Lime Kilns. . . . . . . 121

32 Incremental Annualized Costs for Rotary Lime Kilns to Meet Fine Particle Emission Standards. . . . . . . . . . 122

33 Control Equipment Costs for Municipal Incinerators . . . . 123

34 Incremental Annualized Costs for Municipal Incinerators to Meet Fine Particle Emission Standards . . . . . . . . 124

35 Control Equipment Costs for Iron Foundry Cupolas . . . . . 125

36 Incremental Annualized Costs for Iron Foundry Cupolas to Meet Fine Particle Emission Standards. . . . . . . . . . 126

37 Control Equipment Costs for Primary Aluminum-Electrolytic Cells. . . . . . . . . . . . . . . . . . . . . . . . 128

38 Control Equipment Costs for Primary Copper Plants. . . . . 129

39 Estimates of Fine Particle Emissions as a Function of Emission Standard. . . . . . . . . . . . . . . . . . . 131

40 Projections of Fine Particle Emissions from Industrial Sources. . . . . . . . . . . . . . . . . . . . . . . . 132

41 Example of Economic Impact of Air Pollution Control Requirements on Electric Power Generating Costs. . . . . 137

42 Typical Financial Characteristics of 400-MW Electric Generating Plant . . . . . . . . . . . . . . . . . . . 139

## TABLES (Concluded)

No. Page

43 Estimated Control Costs for 400-MW Electric Generating Plant . . . . . . . . . . . . . . . . . . . . . . . . 140

44 Effect of Control Costs on Costs of Electric Power. . . . 140

45 Effect of Control Criteria on Control Costs in Selected Industries. . . . . . . . . . . . . . . . . . . . . 142

46 Total Annual Cost of Achieving BICD-Level Control of Fine Particulates in Selected Industries. . . . . . . . 143

47 Summary of Fine Particulate Control Costs at BICD-Level Control . . . . . . . . . . . . . . . . . . . . . . 145

48 Unit Value of Output from Selected Industries . . . . . . 146

49 Estimated Damages Resulting from Fine Particle Pollution at an Ambient Concentration of 75 $\mu g/m^3$. . . . . . 155

50 Comparison of Estimated Damages Resulting from Fine Particle Pollution at Ambient Concentrations of 75 and 60 $\mu g/m^3$. . . . . . . . . . . . . . . . . . . . . . . 158

51 Extent of Impact of Uncontrolled Fine Particle Emissions for 400-MW Coal-Fired Electric Plant. . . . . . . . . . 160

52 Economic Costs of Control and Damage Caused by Fine Particulate Emissions at Various Population Densities and Control Efficiencies . . . . . . . . . . . . . 161

53 Economic Costs of Control and Damage Caused by Fine Particulate Emissions . . . . . . . . . . . . . . . . . . 162

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# SECTION I
# SUMMARY

Particles smaller than 2 μ (i.e., fine particulates) are a major factor in air pollution, affecting both human health and the physical properties of the atmosphere. While the overall impact of fine particulate pollutants on man's environment is not precisely quantified, evidence continues to point to many negative features of fine particulate pollution. Realizing the rapidly developing interest in all aspects of the fine particulate pollution problem, the Environmental Protection Agency through its Standards Research Branch contracted with Midwest Research Institute to perform a study to assess the technical and economic feasibility of particulate emission standards based on particle size.

The effort in the current program was directed to an analysis of the technical and economic feasibility of various general bases for emission standards for fine particulates. In practice, the diversity of both the sources and particulate pollutants emitted from various sources will undoubtedly rule out the use of a general emission standard for all sources. However, while the current study is broad in scope, the results have indicated the general feasibility of fine particulate control and the areas for future research and development activity have been pinpointed.

## GOAL(S) FOR PROGRAM TO CONTROL FINE PARTICULATES

Definition of the size of particulates that must be controlled is the first step in formulating a program to reduce the emission of fine particulates. If the aerosol burden in the urban atmosphere is to be reduced, a premium must be placed on the collection of particles smaller than 5 μ. If improved visibility is the goal of fine particulate control, attention must be focused on particle collection in the 0.1-1.0 μ range. Concern for adverse health effects should direct attention to the control of the 0.01-7 μ size range and to the potentially hazardous constituents (e.g., lead, cadmium, mercury) of the effluent stream. Because protection of human health is the main justification for launching a program to control fine particulates, the particle size range below 7 μ is the general size range of interest. Currently available control equipment for particulate pollutants exhibit good collection efficiency down to a particle size of approximately 2 μ. Below this particle size, collection efficiency for most equipment decreases rapidly. Therefore, particles less than 2 μ in diameter are of most interest for future control activities for particulate pollutants.

## APPROACHES FOR REGULATION OF FINE PARTICULATE EMISSIONS

Approaches that could be used to regulate fine particulate emissions include: (1) emission standards; (2) tax incentives; (3) process modifications; (4) substitution of ingredients or fuels; and (5) cessation of processing operations that emit fine particles. The last alternative is deemed untenable except in very special situations. The other alternatives are viable, although methods (3) and (4) are limited in the extent to which they can be used. A precedent exists for utilizing emission standards as the main method of control of fine particulate emissions in the near term. Current programs for the control of particulate pollutants rely on emission standards, and minimum disruption in control agency activities would occur if similar approaches were used for fine particulates. However, the unavailability of high efficiency control equipment and adequate source compliance monitoring methods and/or instrumentation may limit the utility of emission standards--especially if fine particulates must be controlled to a very high degree. Alternative regulatory strategies based on tax incentives might be attractive in that event. Effluent charges or fees for the discharge of fine particulates is one definite possibility. The acquisition of the information necessary to structure an effective and equitable effluent tax will require extensive characterization of both sources and pollutants. While additional data are being obtained to further the formulation of intermediate and long-term strategies for the control of fine particulates, near-term activities could be initiated using emission standards.

Emission standards for the control of fine particulate emissions from industrial sources may be based on factors such as: (1) limitation of the concentration of fine particulates in an effluent stream; (2) specification of the required collection efficiency of control equipment in given particle size ranges; (3) reduction in plume opacity; and (4) limitations of the mass emission rate of fine particulates. Our analysis (see Chapter 4) of the alternative routes for emission standards for fine particulates led to the following conclusions:

1. The use of emission standards based on plume opacity is a practical means for reducing fine particulate emissions in the near term,

2. An emission standard based on the requirement of the installation of the best installed technology on all sources in a specific source category could be implemented in either the near- or intermediate-term, and

3. A mass emission regulation based on the potential emission rate concept is a very attractive approach for the long term.

Emission standards based on plume opacity would require the least amount of additional data acquisition and they would readily interface with existing programs for control of particulate pollutants. An emission standard requiring the installation of the best installed technology would represent the attainment of the current practical limit of control equipment performance. Regulations based on the potential emission rate concept would establish emission limits which vary with the pollution potential of the source, e.g., limitation of mass rate of fine particulate emissions in pounds per hour as a function of potential emission rate, also pounds per hour. A regulation of this type could be tailored to the control of specific sources or specific constituents of a particulate effluent stream. The existing data base on potential emission rates of fine particulates is clearly inadequate for the intelligent selection of allowable emission rates. An extensive data acquisition program will be required to obtain the needed emission rate data before viable standards based on potential emission rate can be developed.

## TECHNICAL IMPLICATIONS OF EMISSION STANDARDS

An analysis of the technical implications of emission standards requiring 10% and 5% plume opacity indicated that currently available control equipment could achieve the required overall collection efficiency. Transmissometers are also available to permit instrumental evaluation of plume opacity. An emission standard based on installation of the best installed technology obviously stretches current technology to near its limit. Only manual methods are currently available for monitoring compliance of sources with a regulation of this type.

Substantial reductions in fine particulate emissions could be achieved by either opacity standards or the installation of best installed technology. Table 1 presents estimates of emission reductions that might be achieved. The estimated reductions in emissions shown in Table 1 assume that the control equipment is in operation 100% of the time that a source is operating. This is seldom the case, but accurate data are generally not available on the reliability of control equipment. The reliability of control equipment will have to be improved if efforts to control fine particulates are to be successful.

Another area in which improvement will be necessary in order to achieve control of fine particulates is the capture efficiency of hooding systems that are associated with many installations of control devices. Capture

Table 1. ESTIMATES OF FINE PARTICLE EMISSIONS AS A FUNCTION OF EMISSION STANDARD

| | Estimated Fine Particle Emissions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Uncontrolled | | Present | | BICD Standard[b] | | 10% Opacity Standard | | 5% Opacity Standard | |
| Source | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year |
| I. Coal combustion | 796,000 | 3,184,000 | 243,000 | 972,000 | 15,000 | 60,000 | 5,050 | 20,200 | 2,510 | 10,040 |
| II. Iron and steel | | | | | | | | | | |
| A. Sinter machines | 7,100 | 28,400 | 1,400 | 5,600 | 64 | 256 | 722 | 2,888 | 354 | 1,416 |
| B. Basic oxygen furnace | 400,000 | 1,600,000 | 43,600 | 174,400 | 2,560 | 10,240 | 1,540 | 6,160 | 800 | 3,200 |
| C. Electric arc furnace | 27,400 | 109,600 | 3,600 | 14,400 | 645 | 2,580 | 1,036 | 4,144 | 683 | 2,732 |
| III. Cement plants, rotary kilns | 243,000 | 972,000 | 44,300 | 177,200 | 2,000 | 8,000 | 25,200 | 100,800 | 12,200 | 48,800 |
| IV. Asphalt plants, dryers | 3,260,000 | 1,956,000 | 257,000 | 154,200 | 25,600 | 15,360 | 200,000 | 120,000 | 167,000 | 100,200 |
| V. Ferroalloy plants | | | | | | | | | | |
| A. Closed electric furnace | 92,000 | 368,000 | 11,300 | 45,200 | 11,300 | 45,200 | NC[a] | NC | NC | NC |
| B. Hooded open electric furnace | 129,500 | 518,000 | 84,100 | 336,400 | 15,800 | 63,200 | NC | NC | NC | NC |
| C. Unhooded open electric furnace | 72,000 | 288,000 | 60,800 | 243,200 | 28,800 | 115,200 | NC | NC | NC | NC |
| VI. Lime plants, rotary kilns | 75,800 | 303,200 | 22,000 | 88,000 | 1,200 | 4,800 | 10,500 | 42,000 | 4,800 | 19,200 |
| VII. Municipal incinerators | 15,000 | 37,500 | 13,100 | 32,800 | 490 | 1,225 | 3,400 | 8,500 | 1,900 | 4,750 |
| VIII. Iron foundry, cupola | 22,900 | 22,900 | 13,100 | 13,100 | 356 | 356 | 5,900 | 5,900 | 4,000 | 4,000 |

---

[a] Not calculated.

[b] BICD - Best installed control device (not necessarily the highest efficiency device available, but rather the best that is generally being installed at present time).

efficiency of hood systems that are necessary for many sources is frequently estimated to be less than 95%. If the control device efficiency is in excess of 99%, the particulate matter which escapes the hooding system becomes very significant.

## ECONOMIC IMPACT OF EMISSION STANDARDS

Requirements for a given level of fine particulate control from stationary sources may have significant economic impacts on an industry, with the extent of the impact depending on the characteristics of the industrial processes involved and on the specific control equipment requirements.

The additional production costs incurred as a result of control practices will include both operating costs and capital charges, again depending on the type of control equipment installed. These costs have been estimated for a variety of industries, with capital charges computed at four different rates to reflect differences in equipment life, depreciation policies, and accounting procedures. In this study estimates of control costs and the resultant impact on production costs were determined for emission standards requiring the achievement of 10% or 5% plume opacity and the installation of best demonstrated technology. Tables 2 to 4 summarize the estimated costs for selected industrial sources. The estimates shown in Table 4 indicate a widely varying impact among the industry studied. In most cases, installation of the best installed technology will have relatively minor effects on overall production costs, generally amounting to less than 1.0% of the value of the product produced.

## BENEFIT/COST RELATIONSHIPS FOR FINE PARTICULATE CONTROL

To assure the optimum utilization of economic resources, the costs of particulate control must be weighed against the benefits realized by having reduced the fine particulate emissions. The economic damages resulting from uncontrolled and controlled fine particulate emissions were investigated, although insufficient data are available to draw any definite conclusions. When adequate data become available through additional research, it will be possible to define the optimum control strategy for any given set of conditions.

For illustrative purposes, the economic losses attributable to interactions between fine particulates at ambient concentrations of 75 and 60 $\mu g/m^3$, and humans, animals, vegetation, materials and aesthetics, were estimated. The estimates were based on the area over which exposure takes place, and on the economic values exposed to damage.

Table 2. EFFECT OF CONTROL CRITERIA ON CONTROL COSTS IN SELECTED INDUSTRIES

| Source | Control Criteria | Fine Particle Control Efficiency (%) | Model Plant Annual Production Rate | Total Annual Control Cost ($1,000) at Specified Capital Charge Rate | | | |
|---|---|---|---|---|---|---|---|
| | | | | 0.15 | 0.17 | 0.20 | 0.30 |
| Coal-fired electric plant | BICD | 98.13 | 2.4 x $10^9$ kwh | 241.5 | 262.1 | 293.0 | 396.0 |
| | 10% Opacity | 99.36 | | 320.0 | 348.0 | 390.0 | 530.0 |
| | 5% Opacity | 99.68 | | 378.5 | 409.9 | 457.0 | 614.0 |
| Municipal incinerator | BICD | 96.71 | 80,000 tons | 35.5 | 38.9 | 44.0 | 61.0 |
| | 10% Opacity | 77.41 | | 25.3 | 27.6 | 31.1 | 42.7 |
| | 5% Opacity | 87.50 | | 29.8 | 32.5 | 36.6 | 50.2 |
| Cement plant (rotary kiln) | BICD | 99.17 | 3.0 x $10^6$ bbls | 125.1 | 134.3 | 148.2 | 194.4 |
| | 10% Opacity | 89.58 | | 89.2 | 98.1 | 111.4 | 155.8 |
| | 5% Opacity | 94.94 | | 98.1 | 107.7 | 122.1 | 170.2 |
| Asphalt plant (rotary dryers) | BICD | 99.21 | 90,000 tons | 13.3 | 14.3 | 15.9 | 21.2 |
| | 10% Opacity | 92.86 | | 20.9 | 21.3 | 22.0 | 24.1 |
| | 5% Opacity | 94.05 | | 31.2 | 31.8 | 32.7 | 35.6 |
| Iron and steel | | | | | | | |
| (a) Basic oxygen furnace | BICD | 99.70 | 1.0 x $10^6$ tons | 211.0 | 230.2 | 259.0 | 355.0 |
| | 10% Opacity | 99.82 | | 227.0 | 247.0 | 277.0 | 377.0 |
| | 5% Opacity | 99.91 | | 255.0 | 274.2 | 303.0 | 399.0 |
| (b) Electric arc furnace | BICD | 97.64 | 100,000 tons | 50.1 | 53.7 | 59.2 | 77.4 |
| | 10% Opacity | 93.54 | | 36.1 | 39.3 | 44.1 | 60.2 |
| | 5% Opacity | 97.24 | | 42.2 | 46.3 | 52.4 | 72.8 |
| (c) Sintering (windbox) | BICD | 99.10 | 1.46 x $10^6$ tons | 277.0 | 297.0 | 327.0 | 427.0 |
| | 10% Opacity | 87.76 | | 184.5 | 199.9 | 223.0 | 300.0 |
| | 5% Opacity | 94.05 | | 204.5 | 221.5 | 247.0 | 332.0 |
| Lime plant (rotary kiln) | BICD | 98.43 | 87,500 tons | 17.5 | 18.9 | 21.0 | 28.0 |
| | 10% Opacity | 78.04 | | 41.6 | 42.4 | 43.7 | 47.9 |
| | 5% Opacity | 90.59 | | 63.4 | 64.6 | 66.3 | 72.1 |
| Iron foundry cupola | BICD | 98.46 | 10,000 tons | 15.1 | 16.3 | 18.1 | 24.2 |
| | 10% Opacity | 74.29 | | 23.8 | 24.3 | 25.2 | 27.9 |
| | 5% Opacity | 82.86 | | 34.5 | 35.2 | 36.3 | 39.7 |

Table 3. TOTAL ANNUAL COST OF ACHIEVING BICD[a]-LEVEL CONTROL OF FINE PARTICULATES IN SELECTED INDUSTRIES

| Source | Model Plant Production Rate/Year | Total Annual Control Cost for Model Plant at Specified Capital Charge Rate ($1,000) | | | | Total Annual Industry Production | Total Annual Control Cost for Industry at Specified Capital Charge Rate ($$10^6$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.15 | 0.17 | 0.20 | 0.30 | | 0.15 | 0.17 | 0.20 | 0.30 |
| Coal-fired electric plant | 2.4 x $10^9$ kwh | 241.5 | 262.1 | 293.0 | 396.0 | 516 x $10^9$ kwh | 51.9 | 56.4 | 63.0 | 85.1 |
| Municipal incinerator | 80,000 tons | 35.5 | 38.9 | 44.0 | 61.0 | 18 x $10^6$ tons | 8.0 | 8.8 | 9.9 | 13.7 |
| Cement plant (rotary kiln) | 3.0 x $10^6$ bbls | 125.1 | 134.3 | 148.2 | 194.4 | 400 x $10^6$ bbls | 16.7 | 17.9 | 19.8 | 25.9 |
| Asphalt plant (rotary dryers) | 90,000 tons | 13.3 | 14.3 | 15.9 | 21.2 | 350 x $10^6$ tons | 51.7 | 55.6 | 61.8 | 82.4 |
| Iron and steel | | | | | | | | | | |
| (a) Basic oxygen furnace | 1.0 x $10^6$ tons | 211.0 | 230.2 | 259.0 | 355.0 | 50 x $10^6$ tons | 10.6 | 11.5 | 13.0 | 17.8 |
| (b) Electric arc furnace | 100,000 tons | 50.1 | 53.7 | 59.2 | 77.4 | 21.5 x $10^6$ tons | 10.8 | 11.5 | 12.7 | 16.6 |
| (c) Sintering (windbox) | 1.46 x $10^6$ tons | 277.0 | 297.0 | 327.0 | 427.0 | 54 x $10^6$ tons | 10.2 | 11.0 | 12.1 | 15.8 |
| Ferroalloy | | | | | | | | | | |
| (a) Unhooded open electric furnace | 8,000 tons | 205.5 | 220.5 | 243.0 | 318.0 | 600,000 tons | 15.4 | 16.5 | 18.2 | 23.9 |
| (b) Hooded open electric furnace | 10,800 tons | 51.4 | 55.2 | 60.8 | 79.6 | 1.08 x $10^6$ tons | 5.1 | 5.5 | 6.1 | 8.0 |
| (c) Closed electric furnace | 13,600 tons | 3.8 | 4.1 | 4.5 | 6.0 | 820,000 tons | 0.2 | 0.2 | 0.3 | 0.4 |
| Lime plant (rotary kiln) | 87,500 tons | 17.5 | 18.9 | 21.0 | 28.0 | 18.5 x $10^6$ tons | 3.7 | 4.0 | 4.4 | 5.9 |
| Iron foundry cupola | 10,000 tons | 15.1 | 16.3 | 18.1 | 24.2 | 13.1 x $10^6$ tons | 19.8 | 21.4 | 23.7 | 31.7 |

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a/ See footnote (b), Table 1, for definition of BICD.

Table 4. SUMMARY OF FINE PARTICULATE CONTROL COSTS AT BICD-LEVEL CONTROL
($/Unit of Production)

| Source | Annual Production Rate for Model Plant | Fine Particle Control Efficiency | Capital Charge Rate 0.15 | 0.17 | 0.20 | 0.30 |
|---|---|---|---|---|---|---|
| Coal-fired electric plant | 2.4 x $10^9$ kwh | 98.13 | 0.00010 | 0.00011 | 0.00012 | 0.00017 |
| Municipal incinerator | 80,000 tons | 96.71 | 0.444 | [illegible]486 | 0.550 | 0.763 |
| Cement plant (rotary kiln) | 3.0 x $10^6$ bbls | 99.17 | 0.042 | 0.045 | 0.049 | 0.065 |
| Asphalt plant (rotary dryers) | 90,000 tons | 99.21 | 0.147 | 0.159 | 0.177 | 0.236 |
| Iron and steel | | | | | | |
| (a) Basic oxygen furnace | 1.0 x $10^6$ tons | 99.70 | 0.211 | 0.230 | 0.259 | 0.355 |
| (b) Electric arc furnace | 100,000 tons | 97.64 | 0.501 | 0.537 | 0.592 | 0.774 |
| (c) Sintering (windbox) | 1.46 x $10^6$ tons | 99.10 | 0.190 | 0.203 | 0.224 | 0.292 |
| Ferroalloy | | | | | | |
| (a) Unhooded open electric furnace | 8,000 tons | 60.00 | 25.688 | 27.563 | 30.375 | 39.750 |
| (b) Hooded open electric furnace | 10,800 tons | 87.80 | 4.759 | 5.107 | 5.630 | 7.370 |
| (c) Closed electric furnace | 13,600 tons | 97.52 | 0.276 | 0.298 | 0.331 | 0.441 |
| Lime plant (rotary kiln) | 87,500 tons | 98.43 | 0.200 | 0.216 | 0.240 | 0.320 |
| Iron foundry cupola | 10,000 tons | 98.46 | 1.512 | 1.613 | 1.814 | 2.418 |
| Primary aluminum (electrolytic cells) | 3,000 tons | 94.85 | 6.52 | 6.99 | 7.71 | 10.08 |
| Primary copper | 76,000 tons | 98.85 | 1.455 | 1.595 | 1.805 | 2.505 |

The most important variable is population density. Total economic losses attributable to sustained exposure at the prescribed concentrations range from about \$5,000/mile$^2$ in sparsely populated rural areas, to well over \$1 million/mile$^2$ in densely populated urban locations, with per capita costs ranging from over \$500 to less than \$30, depending on the characteristics of the area in question.

The control efficiency at which the total of control costs and the costs of remaining damages is a minimum identifies the optimum control level; this is also the point at which incremental control costs equal the incremental benefits of control. A low population density will have a relatively low minimum net cost and will require a relatively low control efficiency. Densely populated areas will experience much higher damage costs, and therefore justify much higher control efficiencies.

The effectiveness of any program for the control of fine particulate emissions must ultimately be judged by improvements in ambient air quality. Because both atmospheric conversion processes (chemical and physical) and sedimentation contribute to the fine particulate burden in the atmosphere, it may be difficult to relate atmospheric levels of fine particulates to control activities on specific sources. For example, in Los Angeles, about 35% of the ambient particulate burden is formed in the atmosphere from gaseous pollutants. In a city like Los Angeles, reductions in emissions of fine particulates from stationary sources would not result in a proportionate decrease in ambient fine particulate concentration. As a consequence, development of meaningful benefit/cost relationships for fine particulate control may be quite difficult in some urban locations. While the assessment of the overall effectiveness of control efforts may be difficult, the total burden of fine particulates entering the atmosphere would nonetheless be reduced by direct limitation of source emissions.

## OVERALL FEASIBILITY OF EMISSION STANDARDS BASED ON PARTICLE SIZE

Our analysis of the implications of emission standards based on particle size has identified some technical deficiencies that will limit the type of standards that can be proposed and implemented in the near future. However, because the technical deficiencies relate primarily to the lack of data on particle size distributions of effluents and control equipment fractional efficiency, there appear to be no insurmountable technical obstacles to emission standards based on particle size.

Although our analysis of various formats for emission standards based on particle size was performed in the context of general regulations that might be applied uniformly to all sources, a more realistic approach would be to tailor the emission standard to specific sources of fine particulate pollutants. Tailoring of standards would permit a greater degree of flexibility in an overall control plan for fine particulates, and would acknowledge the differences in the importance and difficulty of control of individual sources.

The exact format of the emission standard(s) that could be proposed and implemented for specific sources will be limited by: (1) collection efficiency in fine particle size range of available control equipment; and (2) availability of source compliance monitoring techniques.

The economic impact of fine particulate control was found to vary substantially from industry to industry. Estimates of costs associated with the control of fine particulates varied from less than 1.0% up to 20% of the value of the product. The variation in economic impact suggests that it may be necessary to consider less restrictive standards for industries that experience a significant adverse economic impact.

Because our understanding of the damages resulting from fine particulate pollutants is far from complete, definitive statements regarding the benefits that would accrue from improved control of fine particulate emissions cannot be made at this time. In view of our lack of knowledge of benefits resulting from control activities, it seems prudent to consider a long-range strategy based on the adoption and implementation of progressively more stringent regulations for the control of fine particulates. Each step toward more effective control of fine particulates would be based upon improved knowledge of: (1) the effects of fine particulates on human health and welfare; (2) the technical and economic impact of the more stringent regulations; and (3) the benefits that would accrue to society from a further decrease in fine particulate pollution.

# SECTION II
# RECOMMENDATIONS FOR FUTURE WORK

## INTRODUCTION

The existing information base in nearly every aspect of the fine particulate pollution problem is inadequate. Research or data acquisition programs should be formulated and undertaken in several areas, especially: (1) Source Sampling and Monitoring Methods; (2) Fine Particle Emission Rates; (3) Control Technology Evaluation and Development; (4) Analysis of Relationships Between Fine Particle Emissions and Ambient Air Quality; (5) Economic Impact Analysis; and (6) Cost/Benefit Analysis. Specific programs in each of the above categories are delineated in the following sections.

## SOURCE SAMPLING AND MONITORING METHODS

Current capability to sample, size and monitor particulate emissions from stationary sources is inadequate. Research should be initiated to improve this capability. Specific areas of recommended research are:

1. Laboratory and field evaluations of promising methods for the measurement of the concentration and particle size distribution of particulates smaller than about 5 μm. Methods that should be evaluated include impactors, cyclones, beta-tape devices, and piezoelectric crystal devices.

2. Evaluation of optical techniques for monitoring fine particle emissions. Attention should be directed to a comprehensive evaluation of the performance of on-stack transmissometers on a variety of industrial sources.

## FINE PARTICLE EMISSION RATES

Emission factors for fine particulates are nearly nonexistent at the present time. Source testing programs shall be initiated to gather data on:

1. Rates of emission of particulates in the fine particle size range--nominally less than 2 μm.

2. Chemical composition of particles and carrier gas emitted from stationary sources. Emphasis should be placed on trace metals and potentially hazardous compounds.

A portion of this recommended research could be conducted in conjunction with the programs outlined in the preceding section. However, because experience has generally shown that no single sizing device is suitable for all the sampling circumstances encountered in a wide variety of stationary emission sources, individual testing programs may have to be developed for specific classes of sources.

## CONTROL TECHNOLOGY EVALUATION

The ability of currently available control equipment to collect fine particulates is ill-defined. Programs should be developed to obtain basic performance data on particulate control equipment as a function of particle size. Emphasis should be placed on measuring collection efficiencies in the fine particle size range. These programs should be interfaced with those outlined in the preceding sections so that the best measuring techniques are utilized.

## CONTROL TECHNOLOGY DEVELOPMENT

Presently available information indicates that existing control equipment may not be adequate for the collection of fine particulates from many industrial sources. Research and development programs should be formulated to foster new control technology for fine particulates. Attention should be focused in the following areas:

1. Field evaluation of new or novel and emerging control technology.

2. Laboratory and field evaluation of particle conditioning processes which increase the effective size of particles and thus makes them less difficult to capture.

3. Research on methods to improve the performance of existing control equipment.

## ANALYSIS OF RELATIONSHIPS BETWEEN SOURCE EMISSIONS AND AMBIENT AIR QUALITY

The effectiveness of any program for the control of fine particulate emissions will be judged primarily by improvements in ambient air quality. Unfortunately, the fine particulate pollution problem is only partly a primary particle emission problem. Secondary conversion processes may contribute significantly to the fine particulate burden in some areas. Because of the influence of atmospheric conversion processes and sedimentation on the fine particulate burden in the atmosphere, it may be difficult to relate atmospheric fine particulate levels to control activities on specific sources.

Additional research on methods to relate air quality to emission sources is highly recommended. Priority should be given to studies for urban and industrial regions with a high density of fine particulate sources with differing source characteristics.

## ECONOMIC IMPACT ANALYSIS

More refined analysis of the economic impact of fine particulate emission standards should be conducted. One phase of this research activity should focus on the acquisition of more detailed data on the costs of high efficiency control equipment. Costs of particulate control equipment vary widely. The costs cover a range of values because of local conditions and the nature of the particles, the gas stream, equipment size (gas volume), and design collection efficiency. Published average cost figures frequently do not reflect all cost components and fail to illustrate the great range in costs.

Future economic impact analysis should focus on definite urban or industrial regions. If possible the analysis should include consideration of factors such as changes in industry structure, price elasticity in specific industries, and number of potential plant closings.

## COST/BENEFIT ANALYSIS

A more refined analysis of the trade-offs between costs and benefits associated with emission standards based on particle size should be performed. A major part of this activity should be directed to the quantification of the effects of fine particulates on various receptors. At the present time, the lack of data on the damages associated with fine particulate pollution hampers efforts at meaningful cost/benefit analysis.

# SECTION III
# INTRODUCTION

When air pollution became a major concern in the late 1950's and early 1960's, particulate pollutants from industrial processes were among the first to receive attention and to be controlled. While we have succeeded in removing the black cloud from the smoke stack and with it the major fraction of mass emitted from industrial processes, we have not been nearly as successful in eliminating the particulates which cause the major adverse effects--the particulates below about 2 µm in size (i.e., fine particulates).

Fine particulates resulting from man's activity contribute significantly to all the major adverse aspects of air pollution. Fine particles can initiate or contribute to problems related to human health, changes in atmospheric physical properties, and materials soiling and damage. The effects of particulate matter on human health are, for the most part, related to injury to the surfaces of the respiratory system. Particulate material in the respiratory system may produce injury itself, or it may act in conjunction with gases, producing synergistic effects. Such injury may be permanent or temporary. It may be confined to the surface, or it may extend beyond, sometimes producing functional or other alterations.

Fine particulate pollutants also affect the physical properties of the atmosphere. The chemical and physical properties of the atmosphere affected include: its electrical properties; its ability to transmit radiant energy; its ability to convert water vapor to fog, cloud, rain, and snow; its ability to damage and to soil surfaces. Concern with atmospheric transmission of radiant energy encompasses the entire electromagnetic spectrum, but of particular concern is the infrared region, as it affects the terrestrial heat balance; the ultraviolet region, as it affects both biological processes and photochemical reactions in the atmosphere; and the visible spectrum, as it affects both our ability to see things, and our need for artificial illumination.

As man has become more knowledgeable about his environment, he has also become increasingly aware of the importance to his well-being of the action of fine particles. This awareness has resulted in increased attention being focused on fine particulate pollutants by both governmental and scientific groups. Regulations for the control of fine particle emissions from industrial sources are being considered by both federal and state pollution control agencies.

The Standards Research Branch, Implementation Research Division, Environmental Protection Agency, realizing the developing interest in controlling the emission of fine particulate pollutants from industrial operations, initiated a program with Midwest Research Institute (MRI) to conduct a study to define the technical and economic feasibility of particulate emission standards based on particle size. The program was divided into four major areas of effort:

1. Analysis of approaches for regulating fine particle emissions from stationary sources.

2. Definition of technological and economic requirements necessary for implementation of emission standards.

3. Identification of benefits that would accrue if control procedures for fine particulates can be implemented.

4. Assessment of overall feasibility of implementation of fine particle emission standards.

In the following chapters of this report we present a discussion of the nature of fine particulate pollution, a description of the major stationary sources of fine particle emissions, and the results of activities in the four major areas of effort delineated in the previous paragraph. Chapter 2 presents a discussion of the role of fine particles in air pollution, while Chapter 3 contains a description of the major stationary sources of fine particle emissions. Chapters 2 and 3 are included in the report in order to acquaint the reader with the nature, magnitude, and sources of fine particulate pollution. Chapter 4 presents our analysis of approaches for regulating fine particle emissions. The technological and economic implications of fine particle control are presented in Chapters 5 and 6. A general discussion of potential benefits from the control of fine particle emissions is given in Chapter 7. Our assessment of the overall feasibility of emission standards for fine particles and recommendations for future work are given in Chapters 8 and 9.

# SECTION IV
# ROLE OF FINE PARTICLES IN AIR POLLUTION

## INTRODUCTION

Particulate pollutants resulting from man's activity are chemically and physically a most diverse class of substances. They are variously described as grit, dust, fume, smoke, aerosol or smog. The meanings generally given to these terms are listed in Table 5.[1/] In this report the term particulate pollutant is used to mean any dispersed matter, solid or liquid, in which the individual aggregates are larger than single small molecules (about 0.0002 µm in diameter), but smaller than about 500 µm. This is the same definition used in the document, Air Quality Criteria for Particulate Matter.[2/]

Particulate pollutants may remain suspended in the atmosphere for times ranging from a few minutes to many hours. Particulate removal from the atmosphere occurs by diffusion, sedimentation, capture by cloud droplets and scrubbing by precipitation. In the absence of precipitation, sedimentation dominates and the removal of airborne particles from the atmosphere depends upon the aerodynamic particle size of the particles. Figure 1 presents a relationship between particle size (aerodynamic) and the mean residence time for particles in the atmosphere in the absence of precipitation.[3/] As shown in Figure 1, particles in the range of 10 µm to 1 µm have mean residence times of 10-100 hr, while the mean residence time of submicron particles is on the order of $10^2$-$10^3$hr.

A profile of the effects of particulate air pollution in the community is presented in Figure 2. The effects are all related to particle size. Comparison of Figures 1 and 2 indicates that with the exception of soiling or damage of horizontal surfaces, the particles with residence times exceeding 100 hr (i.e., fine particulates) play the most important role.

The overall impact of fine particulate pollutants, broadly defined as particles less than 2 µm in size, on man's environment is not well known.

Table 5. CLASSIFICATION OF PARTICULATE POLLUTANTS1/

| | |
|---|---|
| Grit: | Coarse particles, greater than 76 µm which is the size of the opening in the 200 mesh sieve. |
| Dust: | Particles smaller than 76 µm (i.e., able to pass through a 200 mesh sieve) and larger than 1 µm. |
| Fume: | Solid particles smaller than 1 µm. |
| Mist: | Liquid particles, generally smaller than 10 µm. |
| Fogs: | Mists are sometimes called fogs when they are sufficiently dense to obscure vision. |
| Smoke: | This is the term used generally to describe the waste products from combustion, and may either be fly ash or the products of incomplete combustion, or both. The particles can be liquid or solid. |
| Smog: | A term--a combination of smoke and fog--used to describe any objectionable air pollution. There are two kinds, known as the Los Angeles and the London type. The Los Angeles smog is photo-chemical and comes from motor car exhausts. The London type comes from the incomplete combustion of coal and is characterized by its relatively high sulphur dioxide concentration and particle content. |
| Soot: | Soot is the aggregated particles of unburned carbon produced by incomplete combustion. |
| Aerosols: | Initially this term was used for the fine relatively stable aerial suspensions. In recent years the term has been generally applied to all airborne suspensions. |

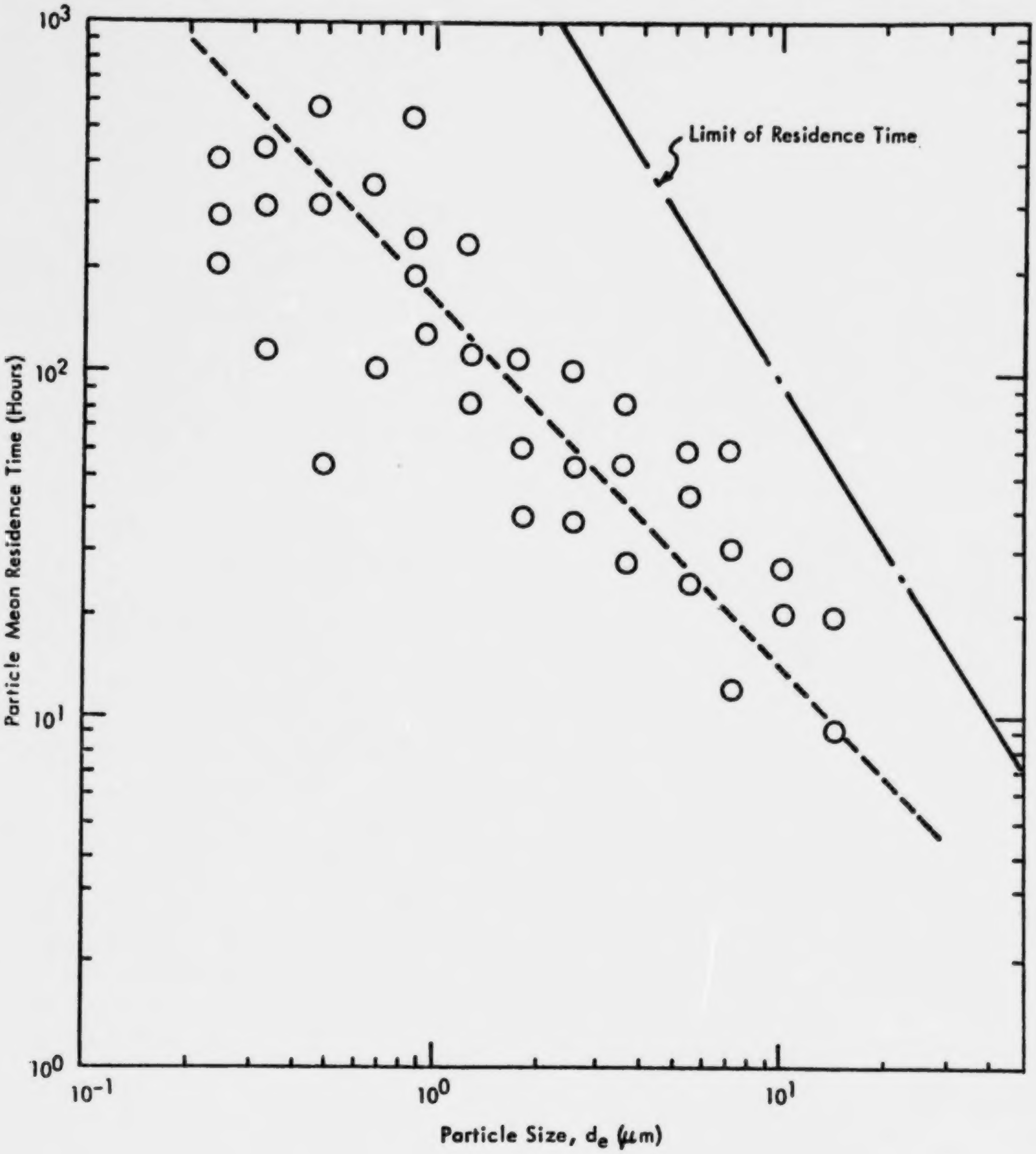

Figure 1. Relationship between particle mean residence time and particle size3/

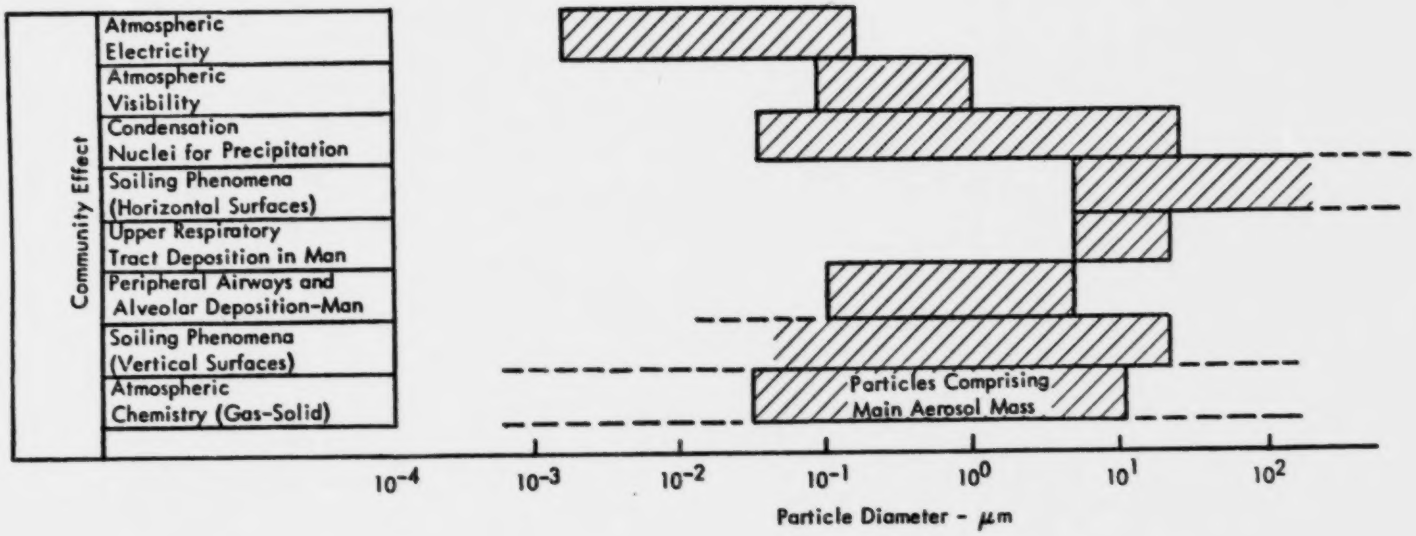

Figure 2. Effects of particulate air pollution in the community as related to particle size4/

However, evidence continues to point to the many negative aspects of fine particle pollution. Research on health effects of air pollution indicate links between fine particulate pollution and health effects of varying severity. In addition to particle size, the chemical composition of particulates is an important factor in determining the effects of this type of air pollution. For example, the health hazard associated with inhaled airborne particles depends on: (1) the site of deposition in the respiratory tract, which is determined by particle size; and (2) the effect on biological tissues at the deposition site, which depends on chemical composition. The hazardous pollutant problem (e.g., mercury, lead, cadmium, vanadium) is also directly linked to fine particle pollution because many of the industrial processes that emit hazardous pollutants liberate them in the form of micron or submicron particles. On both a regional and global scale, fine particulate pollutants play a principal role in the transport through the air of a variety of hazardous substances. It is emphasized that the hazards posed to human health by trace amounts of toxic materials in the form of fine particulates can be disproportionate to the mass involved.

Suspended fine particles may have considerable influence on the behavior of the atmosphere and thus on human activities. Fine particles in the atmosphere absorb and scatter light, decrease visibility, influence solar radiation, and interfere with astronomical observations.

The role of fine particles in air pollution is presented in more detail in the following sections. Health effects will be discussed first, followed by a review of the effects on the physical properties of the atmosphere.

## EFFECTS OF FINE PARTICULATES ON HUMAN HEALTH

Humans as biological organisms with varying degrees of resistance and adaptive capacity continuously struggle with an essentially hostile environment. Anything lowering the resistance of man or increasing the hostility of the environment, decreases his ability to adapt. A number of studies have shown that children and marginal people with poor adaptive ability because of serious lung disease, heart disease, asthma, or other serious chronic diseases, have increased respiratory illness and cardiac and respiratory death rates parallel to the rise in pollution levels. Thus, at every level of pollution and not at some defined threshold, depending on the adaptive reserve of individuals, someone becomes sick and someone's life is shortened.

Any attempt to understand the relationship between air pollutants and human health requires the integration of many diverse factors. The dynamics of small particles, respiratory system and lung dynamics, mechanisms of respiratory and lung disease, area of residence (i.e., urban vs rural), occupation, smoking habits, and age are among the more important elements that dictate the influence of air pollutants on human health. An extensive body of literature exists on the subject, and only a brief review of a small segment of the literature will be presented, to orient the reader.

## Deposition, Retention, and Clearance Processes in the Respiratory System

Laboratory studies of man and other animals show clearly that the deposition, clearance, and retention of inhaled particles is a very complex process, which is only beginning to be understood. Understanding of these phenomena requires knowledge of the following:

1. Mechanisms and efficiencies of particle deposition in the respiratory system,

2. Retention mechanisms,

3. Clearance mechanisms, and

4. Secondary relocation to other sites in the body.

The physical forces which operate to bring about aerosol deposition within the respiratory system vary in magnitude not only with particle size, but also with the air velocities and times of transit of the air from place to place within the system and from moment to moment throughout the breathing cycle. Three mechanisms are of importance in the deposition of particulate matter in the respiratory tract:

1. Inertial impaction - greatest importance in deposition of large particles of high density, and at points in the respiratory system where the direction of flow changes at branching points in the airways,

2. Gravitational settling (sedimentation) - most important in the deposition of large particles or of high-density particles such as dusts of heavy metals, and

3. Diffusion (Brownian motion) - major mechanism for the deposition of small particles (below 0.1 μm) in the lower pulmonary tract.

The effectiveness with which the deposition forces remove particles from the air at various sites depends upon the obstruction encountered, changes in direction of air flow, and the magnitude of particle displacement necessary to remove them from the air stream. The anatomical arrangement and physical dimensions of the respiratory system, transport mechanisms, flow rates and gas mixing, and aerosol particle size are important factors that must be considered in any physical analysis of the deposition of inhaled aerosols.

The Task Group of Lung Dynamics has recently developed a model for the deposition of particles in the respiratory tract.[5] Findeisen's anatomical model[6] was chosen as the basis for the Task Group Model. Calculations, based on the model, of deposition in respiratory compartments are shown in Figure 3. The curves indicate a relationship between the mass median aerodynamic diameter and the gravimetric fraction of the inhaled particles which would be deposited in each anatomical compartment.

Experimental studies of the deposition of inhaled particulate material may be divided into two broad categories. The first group deals with the measurement of total deposition in the respiratory tract, and the second group is concerned with regional deposition within the various areas of the respiratory tract. Details of these experiments are given in Ref. 7. The following points can be made with respect to the overall retention characteristics of the respiratory system:[7]

1. Percentage deposition increases with aerodynamic particle size from a minimum value of about 25% at ~ 0.5 μm and approaches 100% for particles > 5 μm. Particles of different densities and shapes follow the same deposition curve when size is expressed in terms of equivalent diameter of unit-density spheres. Particles larger than 10 μm are essentially all removed in the nasal chamber and therefore have little probability of penetrating to the lungs. Upper respiratory efficiency drops off as size decreases and becomes essentially zero at about 1 μm.

2. The efficiency of particle removal is high being essentially 100% down to around 5 μm. Below this size it falls off to a minimum at about 0.5 μm. It then increases again as the force of precipitation by diffusion increases with further reduction in size. For particles < 0.1 μm, the percentage deposited out of the total respired air approaches, in value, the fraction of tidal volume which reaches the pulmonary air spaces. This fact suggests that the absolute efficiency of alveolar deposition of these submicron particles approaches 100%.

3. Percentage deposition varies with breathing frequency, increasing, for a heterogeneous aerosol, in both directions from a minimum level at frequencies of 15-20 cycles/min. At slower rates, the probability of

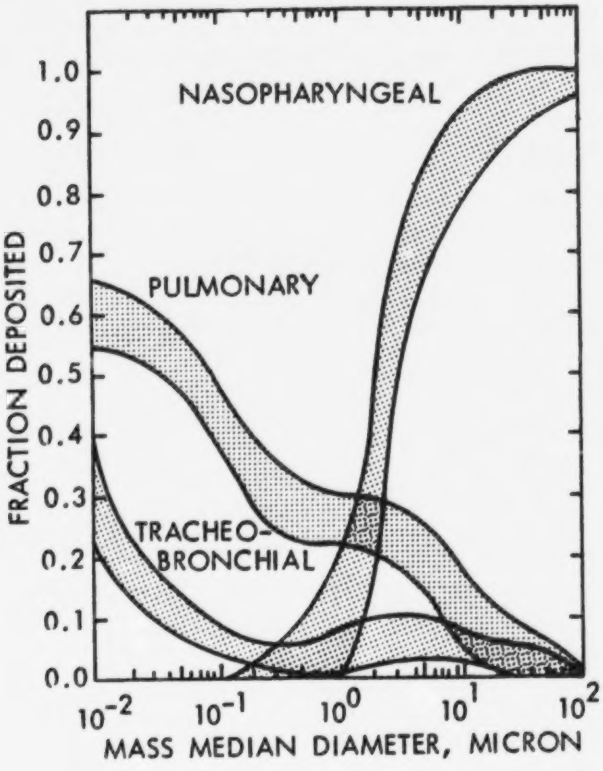

Figure 3. Fraction of particles deposited in the three respiratory tract compartments as a function of particle diameter[5]

deposition by gravity settlement and diffusion goes up in proportion to the increase in transit time of the dust-laden air into and out of the lungs. With more rapid breathing percentage deposition of the coarser particles increases because of the rise in force of inertial deposition with increasing air velocity.

4. Particles of hygroscopic materials are removed in higher percentages than are nonhygroscopic particles of the same (dry) size because of the growth of such particles by water adsorption from the moist air in the respiratory system.

5. There is reasonably good agreement between the directly measured values of overall deposition and the levels predicted from mathematical-physical equations, with respect to both particle size and dynamics of air flow into and out of the respiratory system.

## Clearance of Particulate Matter from the Respiratory System

Different clearance mechanisms operate in the different portions of the respiratory tract, so that the rate of clearance of a particle will depend not only on its physical and chemical properties such as shape and size, but also on the site of initial deposition. The fast phases of the lung clearance mechanisms are different in ciliated and nonciliated regions. In ciliated regions, a flow of mucus transports the particles to the entrance of the gastrointestinal tract, while in the nonciliated pulmonary region, phagocytosis by macrophages can transfer particles to the ciliated region. The rate of clearance is an important factor in determining toxic responses, especially for slow-acting toxicants such as carcinogens. The presence of a nonparticulate irritant or the coexistence of a disease state in the lungs may interfere with the efficiency of clearance mechanisms and thus prolong the residence time of particulate material in a given area of the respiratory tract. In addition, since the clearance of particles from the respiratory system primarily leads to their entrance into the gastrointestinal system, organs remote from the deposition site may be affected.

The Task Group on Lung Dynamics developed a model for respiratory clearance and also summarized experimental work on clearance. Details of the model and the analysis of experimental data are presented in Refs. 2 and 5, and the reader interested in a more complete discussion of respiratory clearance is directed to these sources.

## Toxicological Studies of Atmospheric Particulate Matter

Experimental toxicology develops information on the mode of action of specific pollutants, on the relative potency of pollutants having a similar mode of action, and on the effect of one pollutant on the magnitude of response to another. If man could be used as the experimental subject, experimental toxicology would be the best means of deriving air quality criteria. However, the impossibility of performing experiments using human exposures to varying concentrations of a wide range of compounds precludes this direct approach. A limited amount of intentional human experimentation has been conducted, but most of the data for human toxicology are derived from accidental or occupational exposures.

The use of laboratory animals in toxicological experiments is more straightforward, but the obvious anatomical and metabolic differences between animals and man require the exercise of caution in applying the results of animal exposures to human health criteria. Furthermore, many of the animal experiments have been conducted at exposure concentrations far in excess of those likely to be found in the atmosphere.[8-13]

In spite of these limitations, toxicological studies have shown that atmospheric particles may elicit a pathological or physiological response. Other conclusions from these studies are:

1. The presence of an inert particle in the respiratory tract may interfere with the clearance of other airborne toxic materials,

2. Evaluation of irritant particulates on the basis of mass or concentration alone is not sufficient; data on particle size and number averages per unit volume of carrier gas are needed for adequate interpretation,

3. Particles below 1 μm have a greater irritant potency than larger particles, and

4. A small increase in concentration could produce a greater-than-linear increase in irritant response when the particles are $< 1$ μm.

The possible influence of inert particulate matter on the toxicity of irritant gases has been the subject of considerable speculation and a limited amount of experimental work. Work on the synergistic effects of aerosols and irritant gases is reported in Refs. 14-27. Available information indicates that gases and particulates acting together may cause greater damage than either one acting separately.

Also, if the particulates and gases are delivered in an alternating cycle, the damage is also potentiated. This suggests that the defense evoked by one of the challenges may impair the protection that the lung has against the other. These observations, which admittedly have been made on occasion with greater concentrations of pollutants than normally encountered, should at least alert us to the possibility that a certain ambient particle concentration might be without hazard in an otherwise clean environment, but harmful if respired in association with gases commonly found in an urban environment.

## Epidemiological Studies of Atmospheric Particulate Matter

The ultimate assessment of the impact of air pollution on human health can come only from epidemiology.[28] Because particulate matter and gaseous pollutants tend to occur together in a polluted atmosphere, few epidemiologic studies have been able adequately to differentiate the effects of the two pollutants. Because we do not now have a good epidemiological basis for stating the influence of particulates, only a brief synopsis of epidemiological studies of atmosphere particulate matter will be presented. References 2 and 28 present an extensive review of epidemiological studies, and those seeking more detail are directed to these sources.

Epidemiologic studies of the relationship between pollutant concentrations and their effects on health have used indices varying from disturbance of lung function to death. British studies of acute episodes of increased pollution show excess deaths occurring at smoke levels from 750 $\mu g/m^3$ to 2,000 $\mu g/m^3$. High $SO_2$ levels are, of course, concurrently present. The excesses of mortality are always accompanied by a very large increase in illness, mainly exacerbations of chronic conditions. Similar, but less spectacular, episodes have been reported in New York City.[2]

Winkelstein found in Buffalo that increases in the mortality rate were significantly linked to higher levels of suspended particulate pollution.[29] His studies showed that mortality from all causes, from chronic respiratory diseases, and from gastric carcinoma increased from the lowest of his five levels of pollution (less than 80 $\mu g/m^3$) through the three higher ranges, after the effects of socioeconomic status had been considered. Zeidberg found in Nashville significant increases in all respiratory deaths at soiling levels over 1.1 cohs annual average.[30,31] Neither of these studies took smoking habits into account and the Nashville study only partially allowed for socioeconomic factors.

Studies of illness in relation to residence in more- and less-polluted areas contribute additional information. Fletcher, et al., noted a proportional decline in the production of morning sputum in chronic bronchitics in West London from 1961 to 1966 as smoke pollution in their residence areas declined from 140 $\mu g/m^3$ annual mean.[32] Douglas and Waller found an increase in frequency and severity of lower respiratory illness at smoke and $SO_2$ levels over 130 $\mu g/m^3$ annual average.[33] A study of Lunn, et al. shows similar differences occurring with more morbidity measured between about 100 $\mu g/m^3$ and 200 $\mu g/m^3$ of smoke, and for others between 200 $\mu g/m^3$ and 300 $\mu g/m^3$ annual average.[34]

Physiologic studies of lung function have also been made in both adults and children. On the basis of present limited knowledge it appears that the alterations found may be both temporary and permanent. The observations now available relate to long-term residence in a given area.[34,35] The study reported in Ref. 34 shows reduced pulmonary function in the children living in areas of high dustfall as compared with those living in low dustfall areas. In the Osaka study the dustfall levels were 6.5 $gm/m^2$-month and 13.3 $gm/m^2$-month.[35] Douglas and Waller[33] have shown that there is a three-fold increase in morbidity from lower chest infections in infants younger than 2 years in moderate and high pollution regions, compared to very low pollution regions.

Bates[36] has recently reviewed advanced concepts of lung function and has made an attempt to differentiate in a preliminary way the effects that an inhaled substance may have on the human lung. Figures 4 to 6 present in a diagrammatic form Bates' analyses of the effects of different materials on the major bronchi of the lung, on the terminal bronchioles, and on the alveoli.

In summary, examination of the studies of the potential effects of air pollutants on lung functions and available epidemiologic data indicates that there is an association between air pollution, as measured by both particulate matter and gaseous pollutants, and health effects of varying severity. Increased respiratory disease morbidity is almost certainly related to air pollution, and fine particulates play an important role either along or in combination with gaseous pollutants.

## MODIFICATION OF PROPERTIES OF THE ATMOSPHERE

The emission of fine particles into the atmosphere can increase the suspended particulate burden, modify the properties of the atmosphere, and, as a result, influence many facets of human activity. The suspended atmospheric particles are of four general types. The first are the "light ions" produced in the air by cosmic rays and radioactivity. They consist of small aggregates of molecules having dimensions up to a few molecular diameters. The second important type of particle consists of the so-called "aitken nuclei." These particles range in radius from 2 x $10^{-7}$ cm up to $10^{-4}$ cm. They are particularly prevalent near cities and the earth's surface.

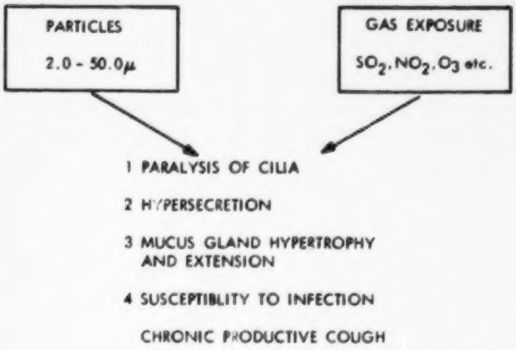
PARTICLES
2.0 - 50.0μ
GAS EXPOSURE
$SO_2, NO_2, O_3$ etc.
1 PARALYSIS OF CILIA
2 HYPERSECRETION
3 MUCUS GLAND HYPERTROPHY AND EXTENSION
4 SUSCEPTIBLITY TO INFECTION
CHRONIC PRODUCTIVE COUGH

Figure 4. Effect of irritants in major bronchi

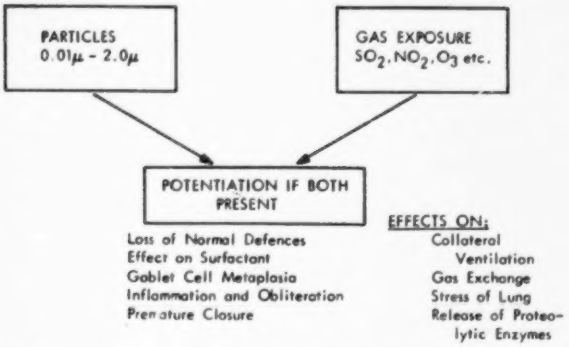
PARTICLES
0.01μ - 2.0μ
GAS EXPOSURE
$SO_2, NO_2, O_3$ etc.
POTENTIATION IF BOTH PRESENT
Loss of Normal Defences
Effect on Surfactant
Goblet Cell Metaplasia
Inflammation and Obliteration
Premature Closure
EFFECTS ON:
Collateral Ventilation
Gas Exchange
Stress of Lung
Release of Proteolytic Enzymes

Figure 5. Effect of irritants in terminal bronchioles

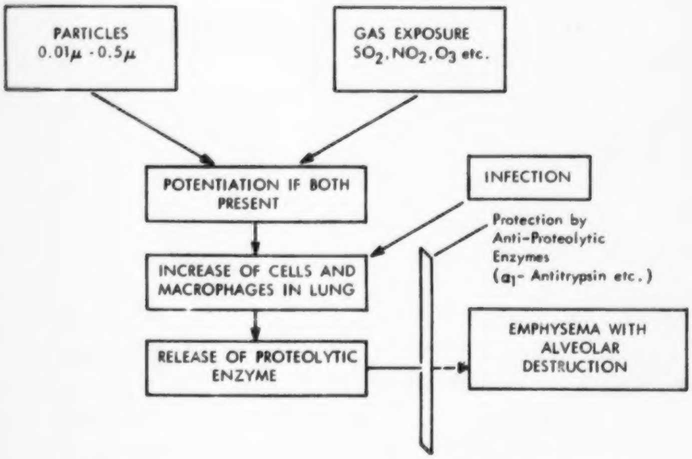
PARTICLES
0.01μ - 0.5μ
GAS EXPOSURE
$SO_2, NO_2, O_3$ etc.
POTENTIATION IF BOTH PRESENT
INFECTION
INCREASE OF CELLS AND MACROPHAGES IN LUNG
Protection by Anti-Proteolytic Enzymes
($a_1$- Antitrypsin etc.)
RELEASE OF PROTEOLYTIC ENZYME
EMPHYSEMA WITH ALVEOLAR DESTRUCTION

Figure 6. Effect of irritants in alveoli

As a rule of thumb, one anticipates finding about 100,000 of these particles per $cm^3$ in a large city, about $10,000/cm^3$ in the country, and about $1,000/cm^3$ at sea. The numbers decrease with increasing altitude and only about 10% of the surface populations are found at an altitude of 7 km. The fine particle pollution of the air is largely composed of these nuclei.

The third type of atmospheric particle is the cloud droplet having a radius from $10^{-4}$ cm to $5 \times 10^{-3}$ cm. Finally, the cloud droplets associate to form raindrops or snowflakes that fall at velocities dependent upon their size. Rain or snow represents the final stage for the removal of atmospheric pollution by natural methods.

The interactions of fine particulate pollutants with atmospheric processes are reviewed in the following sections.

## Visibility

One of the most obvious effects of air pollution is the reduction in visibility which results from the accumulation of particulate matter in the atmosphere. Decreased visibility interferes with certain human activities, such as safe operation of aircraft and automobiles and the enjoyment of scenic vistas. Air pollution that reduces visibility, in addition to endangering the safety of both air and land travel, results in inconvenience and economic loss to the public, and to transportation companies due to disruption of traffic schedules.

Deterioration of visibility caused by suspended particulate matter is the result of adsorption and scattering of light. Both the brightness of the viewed object and its visual contrast with the background are reduced by attenuation of light due to scattering and absorption. In addition, a further contrast reduction results from scattering of sunlight into the observer's line of sight. Loss of brightness and contrast are responsible for the subjective impression of impaired visibility.

Studies of the theory of visibility by numerous authors have led to a very useful relationship between visual range and mass concentration of atmospheric particulate matter. The visual range is defined as the distance, under daylight conditions, at which the apparent contrast between object and background is just equal to the threshold contrast of the observer. The usual assumption of threshold contrast of 0.02 for the human eyes leads to expression[37,38]

$$L = 3.9/b \qquad (1)$$

where L is the visual range in meters and b is the extinction coefficient per meter along the sight path for a black target.

Generally, the extinction coefficient can be depicted as the sum of several components:

$$b = b_{scat} + b_{Rayleigh} + b_{abs\text{-}gas} + b_{abs\text{-}aerosol} \qquad (2)$$

where $b_{scat}$ represents the component due to light scattering by aerosol, $b_{Rayleigh}$ the scattering due to gaseous air (the blue-sky scatter), and $b_{abs\text{-}gas}$ and $b_{abs\text{-}aerosol}$ represent the absorption due to gases (like $NO_2$) and particles (such as carbon black), respectively. Middleton and others have suggested that $b_{scat}$ is dominant especially in situations where the visual range is somewhat degraded due to haze.39/ Measurements of light scatter in urban areas tend to support this assumption.

Mass concentration of atmospheric particulate matter has been found to be approximately proportional to the scattering coefficient, and Charlson, et al.,40/ and Noll, et al.,41/ have developed a useful relationship between visual range and mass concentration of atmospheric particulate matter.

Combining Eq. (1) with the observation that the mass concentration is approximately proportional to "b" results in Eq. (3).

$$L = kM^{-1} \qquad (3)$$

Figures 7 and 8 illustrate visibilities calculated using the above approach.42/ These and other calculations clearly show that, with respect to aerosol particle size, visibility reduction related to air pollution is caused primarily by the 0.1-1.0 µm radius particles.

Most industrial, combustion, and vehicular sources emit particles in a wide variety of sizes. From the preceding discussion, it is clear that the major interest insofar as visibility-reducing particles is concerned centers on those emitted particles in the 0.1-1.0 µm radius range.

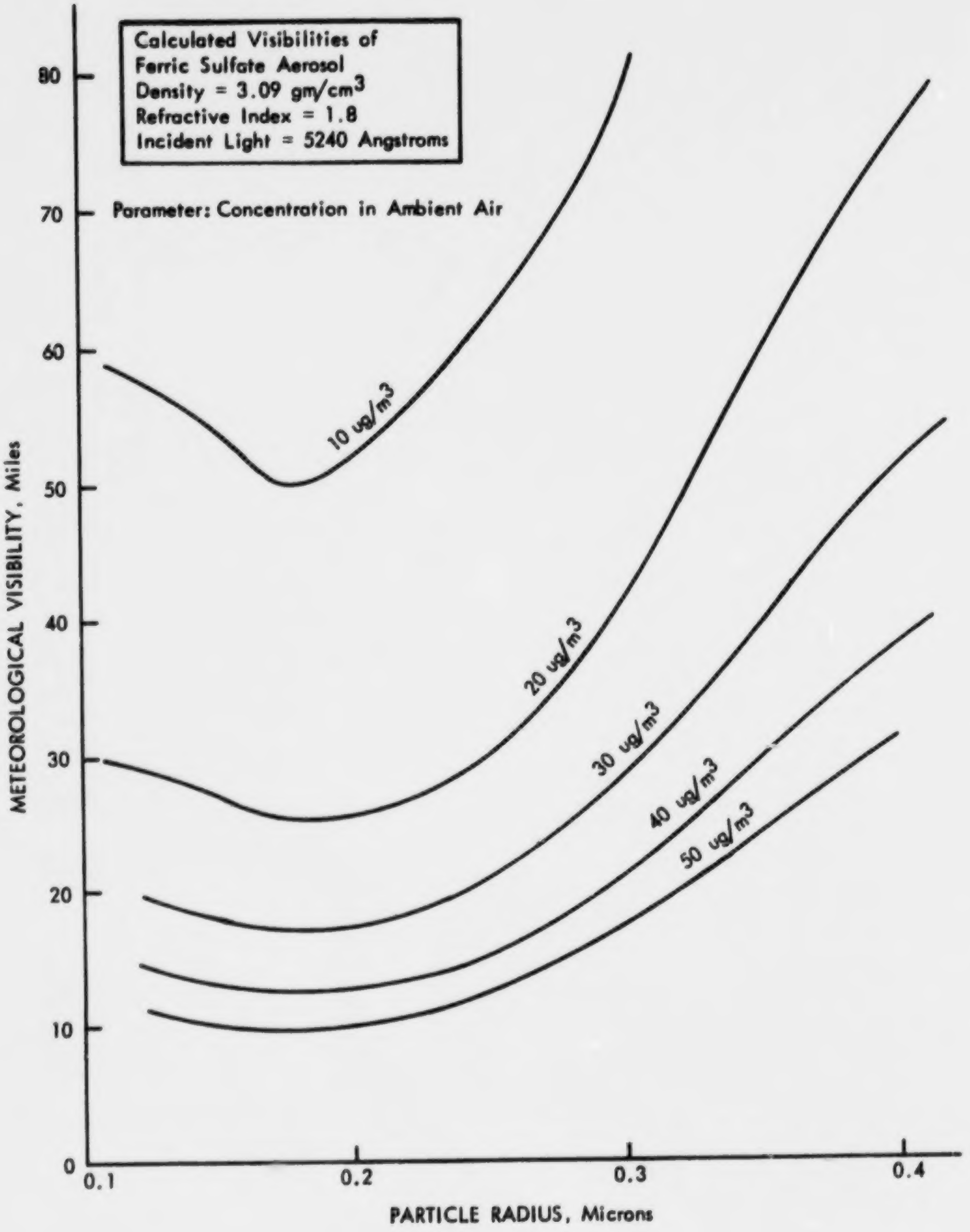

Figure 7. Meteorological visibility vs particle[42] size, ferric sulfate aerosol

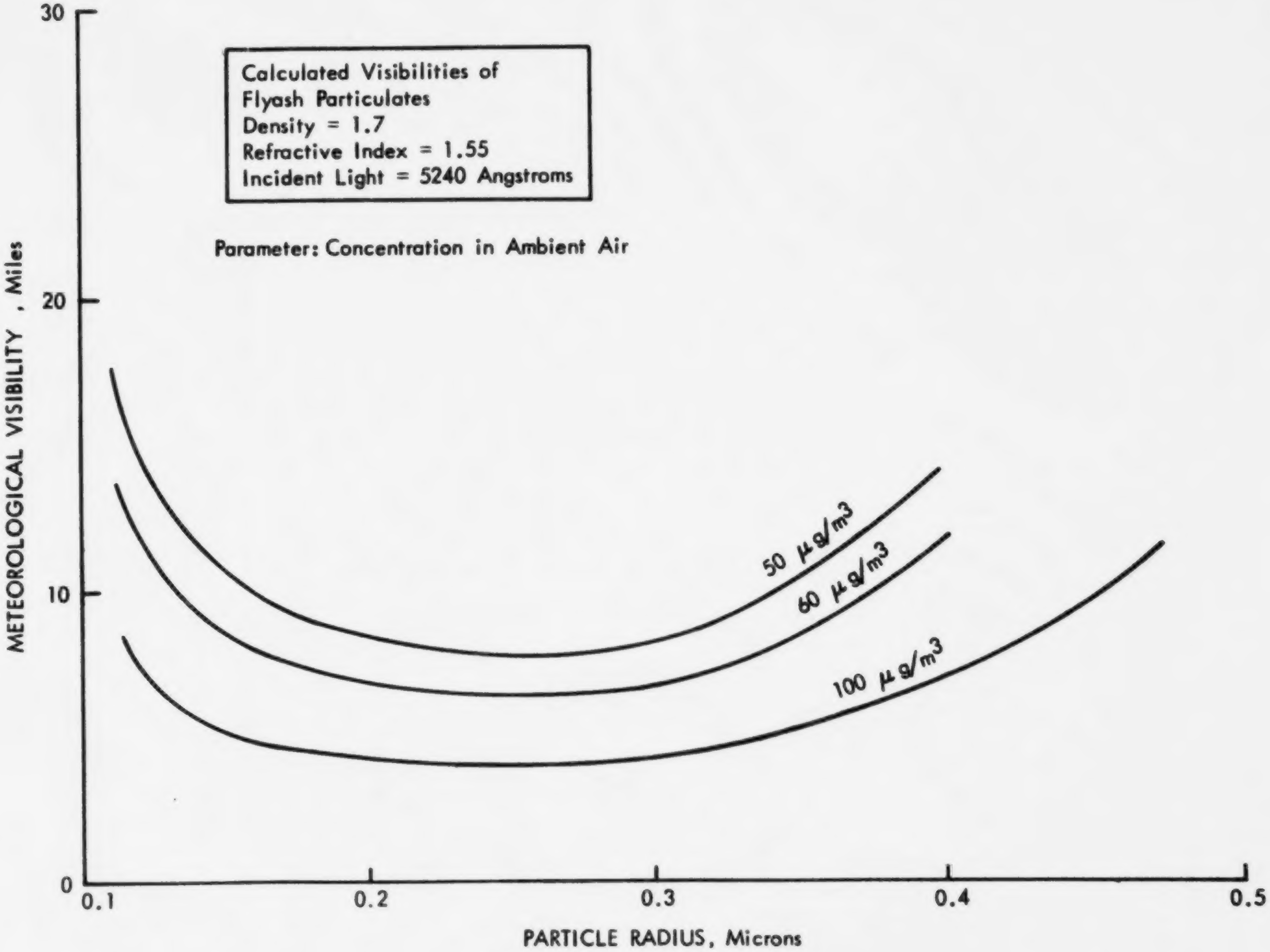

Figure 8. Meteorological visibility vs particle size,42/ flyash aerosol

## Solar Radiation

The intensity and spectral distribution of direct sunlight and scattered daylight, and the variation of intensity with time of day, season, latitude, altitude, and atmospheric conditions are important because they affect photosynthesis in plants and the distribution of plants and animals on earth, the weathering of natural and manmade materials, climate, and illumination for human activity.[43]

The attenuation of solar radiation through the atmosphere is caused by a number of physical factors:[43-45]

1. Rayleigh scattering by air molecules such as $N_2$ and $O_2$, and particles in size ranges less than the wavelength of solar radiation,

2. Selective absorption by gaseous constituents of the atmosphere, and

3. Scattering and absorption by atmospheric dusts and particulate matter of a size greater than the wavelength of solar radiation.

Except in cases of heavy particulate pollution of the atmosphere, such as may occur in large urban centers or heavy industrial areas, it appears that the effect of turbidity is to scatter radiation out of the direct solar beam and add an almost equal amount to the diffuse beam arriving from the rest of the sky by forward-scattering. In cases of heavy particle concentrations, however, the loss from the direct solar beam greatly exceeds the gain in the downward scattered beam, the difference being lost to backscattering off the top of the pollution layer, and to absorption within the polluted layer or column.

Landsberg[46] and Steinhauser[47] report that cities in general receive less solar radiation than do their rural environments. Seasonal, weekly and daily variations in total solar radiation in urban communities have also been noted.[47-49] These variations appear to be related, in part, to cycles of industrial and commercial activity. Measurements at the Moana Loa Observatory in Hawaii, which is remote from any local sources of air pollution, indicate a long-term increase in turbidity or atmospheric dustiness.[50] McCormick and Ludwig have reported significant increases in recent years of turbidity over Washington, D.C., and Davos, Switzerland. Washington and Davos are probably the only localities with reliable records over a 50-year span.[50] Davos is an alpine station far removed from major pollution sources. Cobb reports that man-generated particulate pollution has not yet affected the atmosphere over 90% of the oceans.[51,52] Cobb made his conclusion after comparing electrical conductivity readings taken in the late 1960's with those taken early in the century. Exceptions to the general pattern include paths of anthropogenic aerosol pollution extending from the U.S. across the North Atlantic and from Japan and Asia across the North Pacific. A third path was found across the Indian Ocean, probably caused by monsoon-carried dust. Aerosol concentration is more varied now than it was 60 years ago, according to Cobb. Concentration has doubled over the North Atlantic since 1911 but has remained fairly constant over the South Pacific. Cobb stressed his results show only one aspect of man's effect on the atmosphere, but he is confident that particulate concentration will decline and its influence on climatic conditions will decrease as regulations to reduce the output of particulates are enforced.

Watt has suggested that one way to assess the influence of air pollution on atmospheric properties is to find some natural events in the past that operated in a manner analogous to modern pollution.[53] He analyzed the changes in weather patterns following the eruptions of the Tambora and Krakatau volcanoes, and suggests that these volcanoes had effects similar to the global increase in atmospheric pollution.

The net influence of atmospheric turbidity on surface temperature is uncertain, but the emission of long-lived particles may well be leading to a decrease in world air temperature.[54] As more is learned about the general circulation of the atmosphere and the delicate balance between incoming and outgoing radiation, it seems increasingly probable that small changes such as those occasioned by increasing particle loads in the atmosphere may produce very long-term meteorological effects.

## Weather Modification

Man's knowledge of his ability to inadvertently modify his climate is still at best fragmentary. Insufficient information is known about the long-term build-up of air pollutants, their effects and their interrelationships. Substantial evidence of precipitation modification is meager but significant. An example of increased precipitation from air pollution appears to exist at La Porte, Indiana, some 30 miles downwind from the heavy industrial complex in Chicago. Precipitation and thunderstorm activity have increased significantly since 1925, and precipitation peaks have coincided with peaks in steel production in the Chicago area.[55] Hobbs, et al.,[56] have reported measurements of the concentrations of cloud condensation nuclei in Washington State resulting from pulp and paper mills and other industrial sources. Their study of the precipitation and stream flow records in Washington State for the past 40 years revealed that in recent years there have been significant increases in precipitation in several areas in the vicinity of large industrial sources of cloud-condensation nuclei.

Excessive dustiness in the atmosphere can also reduce rainfall under certain conditions when overseeding occurs. This happens when many small droplets, formed by condensation, do not fall to earth if there is insufficient moisture available to continue the droplet growth by condensation. Consequently, what would have fallen as rainfall stays in the form of clouds. A case in point of this reduction in rainfall has occurred in the sugar producing areas in Queensland, Australia. During the cane harvesting season, the common practice is to burn off the cane leaf before cutting and harvesting. This results in fires over extensive areas and large palls of smoke. The fine smoke particles have modified the cloud formation and hindered the rainfall process. A reduction of up to 25% in the rainfall has occurred downwind of these areas, but there is no such effect in neighboring areas unaffected by the smoke plume.[57] Similar effects have been reported in Puerto Rico, Africa, and Hawaii.[58,59] Schaefer has also reported on observations of changes in micro-physics of clouds in the vicinity of large cities during airplane flights through convective clouds.[58] His observations suggest that such clouds contain an increasing number of cloud droplets. Schaefer's investigations of snow and rainstorm patterns in New York State indicate that submicroscopic particulates from manmade pollution may be initiating and controlling precipitation in a primary manner, rather than being involved in the secondary process wherein precipitation elements coming from natural mechanisms serve to remove the particles by diffusion, collision, and similar scavenging processes.

In summary, available data indicate that man has detectably changed the constitution of the atmosphere; in some respects globally, in another at least on a subcontinental scale, in some cases locally. At the same time, there have been variations of climate. Our present knowledge of atmospheric processes suggests that these changes are what would be expected to follow from man's interference with the atmosphere. But they are also quite compatible with what we know of the statistics appropriate to an atmosphere of undisturbed constitution and they are also compatible with the possible behavior of a dynamical system as complex as the atmosphere.

# SECTION V
# SOURCES OF FINE PARTICULATE EMISSIONS

## NATURE OF THE PARTICULATE POLLUTION PROBLEM

Atmospheric particulate matter can be classified as primary--introduced into the atmosphere in particulate form, or secondary--formed in the atmosphere by chemical and physical processes. Atmospheric particulate matter originates from natural causes such as the sea, volcanoes, and the soil and from man-made sources such as industrial processes and internal combustion engines. In order to cast the particulate pollution problem in the proper perspective, it is helpful to identify the relative contributions of primary particulates from natural and man-made sources.

Tables 6, 7, and 8 summarize estimates of primary particulate emissions from both natural and man-made sources. These estimates were prepared by MRI as part of the work performed on a systems study of particulate pollution.60-62/ Specific details of the procedures used to obtain the estimates are presented in Ref. 60. Estimated emissions from various industrial operations are shown in Table 6. The emissions were computed in most cases by means of the following equation:

$$E = \frac{(P)\ (e_f)\ \ (1 - C_c C_t)}{2,000}$$

where,

$E$ is the emissions rate, tons/year

$e_f$ is the emission factor (uncontrolled), pounds/ton

$P$ is the production rate, tons/year

$C_c$ is the average efficiency of control equipment

$C_t$ is the percentage of the production capacity on which control equipment has been installed

### Table 6. MAJOR INDUSTRIAL SOURCES OF PARTICULATE POLLUTION[60]

| | Source | Emissions (tons/year) |
|---|---|---|
| 1. | Fuel combustion | 5,953,000 |
| 2. | Crushed stone, sand and gravel | 4,600,000 |
| 3. | Agricultural operations (grain elevators, feed mills and cotton gins) | 1,817,000 |
| 4. | Iron and steel | 1,442,000 |
| 5. | Cement | 934,000 |
| 6. | Forest products | 580,000 |
| 7. | Lime | 573,000 |
| 8. | Clay | 467,000 |
| 9. | Primary nonferrous (copper, aluminum, zinc and lead) | 476,000 |
| 10. | Fertilizer and phosphate rock | 328,000 |
| 11. | Asphalt (batch plants and roofing) | 218,000 |
| 12. | Ferroalloy | 160,000 |
| 13. | Iron foundries | 143,000 |
| 14. | Secondary nonferrous (copper, aluminum, zinc and lead) | 127,000 |
| 15. | Coal cleaning | 94,000 |
| 16. | Carbon black | 93,000 |
| 17. | Petroleum | 45,000 |
| 18. | Acids (sulfuric and phosphoric) | 16,000 |
| | Total | 18,056,000 |

Table 7. NONINDUSTRIAL SOURCES OF PARTICULATE POLLUTION[60]

| Source | Emissions (tons/year) | |
|---|---|---|
| A. Natural dusts | | 63,000,000 |
| B. Forest fires | | |
| 1. Wildfire | 37,000,000 | |
| 2. Controlled fire | | |
| (a) Slash burning | 6,000,000 | |
| (b) Accumulated litter | 11,000,000 | |
| 3. Agricultural burning | 2,400,000 | 56,400,000 |
| C. Transportation | | |
| 1. Motor vehicles | | |
| (a) Gasoline | 420,000 | |
| (b) Diesel | 260,000 | |
| 2. Aircraft | 30,000 | |
| 3. Railroads | 220,000 | |
| 4. Water transport | 150,000 | |
| 5. Nonhighway use | | |
| (a) Agriculture | 79,000 | |
| (b) Commercial | 12,000 | |
| (c) Construction | 3,000 | |
| (d) Other | 26,000 | 1,200,000 |
| D. Incineration | | |
| 1. Municipal incineration | 98,000 | |
| 2. On-site incineration | 185,000 | |
| 3. Wigwam burners (excluding forest products disposal) | 35,000 | |
| 4. Open dump | 613,000 | 931,000 |
| E. Other minor sources | | |
| 1. Ruber from tires | 300,000 | |
| 2. Cigarette smoke | 230,000 | |
| 3. Cosmic dust | 24,000 | |
| 4. Aerosols from spray cans | 390,000 | |
| 5. Ocean salt spray | 340,000 | 1,284,000 |
| Total | | 122,815,000 |

Table 8. ALL MAJOR SOURCES OF PARTICULATE POLLUTION

| Source | Emissions (tons/year) | Percent by Weight |
|---|---|---|
| Natural dusts | 63,000,000 | 44.7 |
| Forest fires | 56,400,000 | 40.1 |
| Major stationary industrial sources | 18,056,000 | 12.9 |
| Transportation | 1,200,000 | 0.8 |
| Incineration | 931,000 | 0.7 |
| Other sources | 1,284,000 | 0.8 |
| Total | 140,874,000 | 100.0 |

Production data for 1968 and application of control information* from 1969-1970 were used in the calculations. Table 7 lists nonindustrial sources of particulate pollutants with their corresponding estimated emissions, while Table 8 presents a comparison of particulate emissions from industrial and nonindustrial sources.

As shown in Tables 7 and 8, the largest sources of particulates are natural dusts and forest fires. These sources account for an estimated 85% of the national atmospheric primary particulate loading on a mass basis, and are a substantial portion of background levels. Emissions from these sources are essentially beyond the scope of present air pollution control methodology. Furthermore, their effect on the population is less than for man-made sources because of the concentration of the latter in urban areas.

While the emission figures presented in Table 6 provide some indication of the relative impact of individual industrial operations on the particulate pollution burden, total mass emission data do not clearly portray the really important and serious aspect of particulate air pollution. Not reflected in Table 6 is the relative contribution that the emissions make to the long-lived suspended particulate levels in the atmosphere. As was indicated in Chapter 2, it is the long-lived particles (i.e., fine particulates) that contribute to all the major adverse aspects of particulate air pollution.

## PRINCIPAL SOURCES OF FINE PARTICULATES

As part of the systems study on particulate pollution, MRI estimated the magnitude of the fine particle burden emanating from various particulate pollutant sources.[61] In this work, the fine particle size range was defined as 0.01-2 μm. In making the estimates of fine particle emissions, the best data currently available on particle size distributions before and after control devices, fractional efficiency curves for control devices, and the degree of application of control equipment on specific sources was used to estimate the present level of fine particle emissions from particulate pollution sources.

The method used to calculate the quantity of fine particle emissions is similar to that used in calculating total mass emission in Table 6. The same production figures and emission factors were used. However, to calculate the quantity of fine particles (< 2 μm) emitted it was necessary to use the following additional factors:

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* Application of control is defined as that fraction of the total production which has particulate pollution controls.

a. Particle-size distributions for particulates emitted by uncontrolled sources.

b. Percent application of control on specific sources, with a breakdown of this percent application of control into the percent application of each type of control device.

c. Fractional efficiency characteristics of each type of control device.

Specific details of the calculations are given in Ref. 61.

Table 9 summarizes the estimates of fine particle emissions on the basis of mass emitted in specific particle size ranges. Because of the lack of adequate data on many specific process sources, the emission figures given in Table 9 are not complete for some industrial categories. Also, fine particle emissions for several sources (e.g., crushed stone operations) could not be calculated for each size range shown in Table 9, and fine particle emissions for potentially significant industrial categories, such as primary nonferrous metallurgy and clay products, could not be estimated because of incomplete data. Fine particle emissions from the industrial sources listed in Table 9 are estimated to be at least $4 \times 10^6$ tons/year. This represents approximately 20-25% of the total mass emissions (Table 6) from these sources. In view of the limitations of available data, the figure of $4 \times 10^6$ tons/year of fine particulate emissions from industrial sources probably understates the fine particle burden emanating from those sources.

To indicate the relative magnitude of the fine particle problem from stationary sources, fine particle emissions were also estimated for mobile sources. Particulate emissions from mobile sources were assumed to be uncontrolled and to consist of all $< 2$ μm particulates. Table 10 summarizes the estimate of fine particle emissions from these sources. Fine particle emissions from natural dusts, forest fires, and agricultural burning could not be estimated because of lack of reliable particle size data.61/

Summary of Fine Particle Emissions

Fine particle emissions (primary particulates) from man's activity are conservatively estimated to be over $5 \times 10^6$ tons/year of which about 75% results from stationary industrial operations. Furthermore, these emissions compose about 25% of the total mass of particulates emitted from industrial sources. Stationary combustion and metallurgical operations account for about 50% of the quantity of fine particulates emitted from stationary sources.

Table 9. FINE PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES[61]
(Mass Basis, $10^3$ Tons/Year)

| | Fine Particle Size Ranges (μm) | | | | | |
|---|---|---|---|---|---|---|
| Source | 1-3 | 0.5-1.0 | 0.1-0.5 | 0.05-0.1 | 0.01-0.05 | Total |
| 1. Stationary combustion | | | | | | |
| A. Coal | | | | | | |
| 1. Electric utility | | | | | | |
| a. Pulverized | 591.6 | 178.6 | 99.2 | 2.9 | | 872.3 |
| b. Stoker | 21.7 | 5.7 | 2.2 | | | 29.6 |
| c. Cyclone | 48.2 | 13.9 | 7.3 | 0.2 | | 69.6 |
| | | Total from electric utility | | | | 971.5 |
| 2. Industrial | | | | | | |
| a. Pulverized | 15.1 | 0.5 | | | | 15.6 |
| b. Stoker | 56.6 | 7.3 | 2.1 | | | 66.0 |
| c. Cyclone | 13.5 | 6.7 | 4.1 | 0.1 | | 24.4 |
| | | Total from industrial coal | | | | 106.0 |
| B. Fuel oil | | | | | | |
| 1. Electric utility and industrial | 126.9 | | | | | 126.9 |
| C. Natural gas and LPG | | | | | | |
| 1. Electric utility and industrial | 97.2 | | | | | 97.2 |
| | | Total from fuel oil and gas | | | | 224.1 |
| | | Total from fuel combustion | | | | 1,301.6 |

Table 9. (Continued) FINE PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES[61/]

| Source | Fine Particle Size Ranges (µm) | | | | | |
|---|---|---|---|---|---|---|
| | 1-3 | 0.5-1.0 | 0.1-0.5 | 0.05-0.1 | 0.01-0.05 | Total |
| 2. Crushed stone | 868.0 | | | | | 868.0 |
| 3. Iron and steel | | | | | | |
| A. Sinter machines | 3.8 | 1.2 | 0.6 | | | 5.6 |
| B. Open hearth furnace | 60-80 | 20-56 | 8.5-234 | 0.1-22 | 0-3.6 | 108-376 |
| C. Basic oxygen furnace | 0.9 | 18.9 | 153.7 | 1.0 | | 174.5 |
| D. Electric arc furnace | 3.8 | 2.5 | 5.2 | 1.3 | 1.5 | 14.3 |
| Total from iron and steel | | | | | | 302.4-570.4 |
| 4. Kraft pulp mills | | | | | | |
| A. Bark boilers | 49.1 | 11.9 | 6.5 | 0.3 | | 67.8 |
| B. Recovery furnace | 95.3 | 78.0 | 74.7 | 1.4 | | 249.4 |
| C. Lime kiln | 1.6 | 0.2 | | | | 1.8 |
| Total from kraft pulp mills | | | | | | 319.0 |
| 5. Cement plants, rotary kilns | 130.8 | 32.7 | 13.5 | | | 177.0 |
| 6. Hot-mix asphalt plants | | | | | | |
| A. Rotary dryer | 96.4 | 36.3 | 21.5 | | | 154.2 |
| B. Ventline | 14.4 | 1.7 | 0.2 | | | 16.3 |
| Total from hot-mix asphalt plants | | | | | | 170.5 |
| 7. Ferroalloys | | | | | | |
| A. Electric furnace | 18.4 | 27.8 | 81.1 | 17.3 | 7.7 | 152.3 |
| B. Blast furnace | 0.8 | | | | | 0.8 |
| Total from ferroalloys | | | | | | 153.1 |

Table 9. (Concluded) FINE PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES[61]

| | Fine Particle Size Ranges (μm) | | | | | |
|---|---|---|---|---|---|---|
| Source | 1-3 | 0.5-1.0 | 0.1-0.5 | 0.05-0.1 | 0.01-0.05 | Total |
| 8. Lime plants | | | | | | |
| A. Rotary kilns | 40.6 | 18.8 | 23.6 | 3.0 | 1.8 | 87.8 |
| B. Crushing and screening | 25-99 | | | | | 25.0 |
| Total from lime plants | | | | | | 113.0 |
| 9. Secondary nonferrous metallurgy | 127.0 | | | | | 127.0 |
| 10. Carbon black | 93.0 | | | | | 93.0 |
| 11. Coal preparation plants, thermal dryer | 63.5 | | | | | 63.5 |
| 12. Petroleum FCC units | 45.0 | | | | | 45.0 |
| 13. Municipal incinerators | 10.4 | 6.7 | 11.5 | 3.5 | 4.3 | 36.4 |
| 14. Fertilizer, granulators and dryers | 7.1 | 3.5 | 3.1 | | | 13.7 |
| 15. Iron foundries, cupolas | 6.8 | 2.4 | 3.1 | 0.4 | 0.4 | 13.1 |
| 16. Acids | | | | | | |
| A. Sulfuric | 2.7 | | | | | 2.7 |
| B. Phosphoric (thermal) | 1.0 | | | | | 1.0 |
| Total from acids | | | | | | 3.7 |
| Total from major industrial sources | | | | | | 3,800-4,142 |

Note: Potentially significant sources not evaluated because of lack of sufficient data: (1) operations related to agriculture, (2) primary nonferrous metallurgy, (3) clay products, (4) food processing operations, and (5) fiberglass manufacture.

## Table 10. FINE PARTICLE EMISSIONS FROM MOBILE SOURCES

| Source | Emissions (Tons/Year) |
|---|---|
| 1. Motor vehicles | |
| a. Gasoline | 420,000 |
| b. Diesel | 260,000 |
| 2. Aircraft | 30,000 |
| 3. Railroads | 220,000 |
| 4. Water transport | 150,000 |
| 5. Nonhighway use | |
| a. Agriculture | 79,000 |
| b. Commercial | 12,000 |
| c. Construction | 3,000 |
| d. Other | 26,000 |
| Total | 1,200,000 |

## PRIORITY LIST FOR SOURCES OF FINE PARTICLE EMISSIONS

A complete description of the importance of a given source of fine particulate emissions requires not only the quantification of the amount of fine particulate emitted, but also the identification of the chemical composition of the individual particle size fractions. Attention must be directed to the chemical nature of the particles as it relates to toxicity or hazardous aspects. For example, power plant flyash produced by the combustion of pulverized coal consists of a diverse mixture of metal oxides and silica while cement kilns produce little in the way of potentially hazardous or toxic particulates. Other sources produce different mixtures of substances. Incorporation of considerations of both quantity of fine particulate emissions and chemical composition of particles can lead to a priority ranking of sources of fine particulate emissions.

Data on the chemical composition of various particle size fractions emitted from industrial sources are sketchy at best. However, the limited information available indicates that many of the potentially hazardous materials (e.g., trace metals) are generally in the micron to submicron particle size range. While lack of detailed data hinders the clear-cut identification of the most important sources of fine particulate pollution, available information can be used to develop a relative priority list of emission sources. By using available data on the mass of fine particles emitted by sources, the amount and type of potentially hazardous pollutant emitted by sources, and the general location of sources (i.e., urban or rural), a general profile of the "adverse or negative" characteristics of the particulate pollutants emitted by major industrial sources of fine particles can be developed. Table 11 presents such a profile.

The data on the quantity of fine particles emitted from sources (column 1, Table 11) were taken from Ref. 61, while the information on the amount and type of potentially hazardous pollutant emitted was obtained from Ref. 63. In analyzing the data from Refs. 61 and 63, there appeared to be some difference in the definition of particulate. Reference 61 considered only primary particulates with no consideration of secondary particulates formed by condensation or reaction in the atmosphere. Reference 63 apparently includes particulates formed by condensation.

Since some of the potentially hazardous pollutants may be emitted from a source as a vapor which subsequently condenses in the atmosphere, some sources deemed important in Ref. 63 were not considered in Ref. 61. This accounts for some of the information gaps in Table 11. In addition, the mass of fine particles emitted from some sources listed in Table 11 could not be determined because of lack of sufficient data on the particle size distributions of the emitted particulates.

Table 11. PROFILE OF THE CHARACTERISTICS OF PARTICULATE POLLUTANTS EMITTED BY VARIOUS INDUSTRIAL SOURCES

| Industry and/or Source | Mass of Fine Particles Emitted ($10^3$ tons/year) | Amount of Potentially Hazardous Pollutant Emitted (tons/year) | Type of Potentially Hazardous Particulate Pollutant Emitted | General Plant Location |
|---|---|---|---|---|
| I. Stationary combustion | | | | |
| A. Coal | | | | |
| 1. Electric utility | | | | |
| a. Pulverized | 872.3 | 51,471 | Inorganic/metal oxides, fluorides, polyorganics, As, Ba, Be, B, Cr, Cu, Pb, Mn, Hg, Ni, Se, Sn, V, Zn | Urban, rural |
| b. Stoker | 29.6 | 5,994 | As, Ba, Be, B, Cr, Cu, fluorides, Pb, Mn, Hg, Ni, POM, Se, Sn, V, Zn | Urban, rural |
| c. Cyclone | 69.6 | 1,776 | As, Ba, Be, B, Cr, Cu, fluorides, Pb, Mn, Hg, Ni, POM, Se, Sn, V, Zn | Urban, rural |
| 2. Industrial | | | | |
| a. Pulverized | 15.6 | 3,783 | As, Ba, Be, B, Cr, Cu, fluorides, Pb, Mn, Hg, Ni, POM, Se, Sn, V, Zn | Urban |
| b. Stoker | 66.0 | 13,237 | As, Ba, Be, B, Cr, Cu, fluorides, Pb, Mn, Hg, Ni, POM, Se, Sn, V, Zn | Urban |
| c. Cyclone | 24.4 | 1,891 | As, Ba, Be, B, Cr, Cu, fluoride, Pb, Mn, Hg, Ni, POM, Se, Sn, V, Zn | Urban |
| 3. Commercial and residential | - | 657 | As, Ba, Be, B, Cr, Cu, fluoride, Pb, Mn, Hg, Ni, POM, Se, Sn, V, Zn | Urban, rural |

Table 11 (Continued). PROFILE OF THE CHARACTERISTICS OF PARTICULATE POLLUTANTS EMITTED BY VARIOUS INDUSTRIAL SOURCES

| Industry and/or Source | Mass of Fine Particles Emitted ($10^3$ tons/year) | Amount of Potentially Hazardous Pollutant Emitted (tons/year) | Type of Potentially Hazardous Particulate Pollutant Emitted | General Plant Location |
|---|---|---|---|---|
| B. Fuel oil | | | | |
| 1. Electric utility and industrial | 126.9 | 28,326 | Inorganic/metal oxides, polyorganics, As, Ba, Be, Cr, Cu, Pb, Mn, Hg, Ni, Se, V, Zn | Urban, rural |
| 2. Commercial and residential | - | 44,063 | Ba, Be, Cr, Cu, Pb, Mn, Hg, Ni, POM, Se, Sn, V, Zn | Urban, rural |
| C. Natural gas | | | | |
| 1. Electric utility and industrial | 97.2 | 20,204 | - | Urban, rural |
| 2. Commercial and residential | - | 10,065 | - | Urban, rural |
| II. Crushed stone | 868.0 | - | - | Predominantly rural |
| III. Iron and steel | | | | |
| A. Sinter machines | 5.6 | - | Metal oxides, alkalis | Urban |
| B. Open hearth furnace | 376.0 | 68,227 | Ba, Pb, Mn, Hg, Sn, V, Zn oxides, fluorides, POM | Urban |
| C. Blast furnace | - | 7,215 | As, Cd, Mn, Hg, Ni, V, Zn oxides, fluorides, POM | Urban |
| D. BOF | 175.0 | 2,057 | Ba, fluorides, Mn, Hg, POM, V, Zn | Urban |
| E. Electric arc furnace | 14.3 | 12,508 | Ba, Mn, Hg, Zn | Urban |
| F. Metallurgical coke | - | 43,380 | POM | Urban |

Table 11 (Continued). PROFILE OF THE CHARACTERISTICS OF PARTICULATE POLLUTANTS EMITTED BY VARIOUS INDUSTRIAL SOURCES

| Industry and/or Source | Mass of Fine Particles Emitted ($10^3$ tons/year) | Amount of Potentially Hazardous Pollutant Emitted (tons/year) | Type of Potentially Hazardous Particulate Pollutant Emitted | General Plant Location |
|---|---|---|---|---|
| IV. Kraft pulp mills | | | | |
| A. Bark boiler | 67.8 | - | - | Urban, rural |
| B. Recovery furnace | 249.4 | 15 | Cr, Hg, POM | Urban, rural |
| C. Lime kiln | 1.8 | - | - | Urban, rural |
| V. Cement plants, rotary kilns | 177.0 | 270 | Fluorides | Primarily rural |
| VI. Hot-mix asphalt plants | | | | |
| A. Rotary dryer | 154.2 | 2,800 | POM | Urban, rural |
| VII. Ferroalloys | | | | |
| A. Electric furnace | 152.3 | 4,382 | Mn, Ni, POM, V, Zn | Urban |
| B. Blast furnace | 0.8 | 4,104 | Mn, Ni, Zn, O, POM | Urban |
| VIII. Lime plants | | | | |
| A. Rotary kilns | 87.8 | - | - | - |
| IX. Municipal incinerators | 36.4 | 34,307 | As, Cd, Cu, Pb, Hg, POM, Se, Zn | Urban |
| X. Iron foundry cupolas | 13.1 | 6,151 | As, Ba, Be, Pb, Mn, Hg, Ni, V, Zn oxides, POM, fluorides | Urban |
| XI. Primary copper | | | | |
| A. Roasting | - | 4,373 | As, Cd, Cu, fluoride, Pb, Se | Rural |
| B. Reverberatory furnace | - | 1,885 | As, Cd, Cu, fluoride, Pb, Se | Rural |

Table 11 (Concluded). PROFILE OF THE CHARACTERISTICS OF PARTICULATE POLLUTANTS EMITTED BY VARIOUS INDUSTRIAL SOURCES

| Industry and/or Source | Mass of Fine Particles Emitted ($10^3$ tons/year) | Amount of Potentially Hazardous Pollutant Emitted (tons/year) | Type of Potentially Hazardous Particulate Pollutant Emitted | General Plant Location |
|---|---|---|---|---|
| C. Converters | - | 5,591 | As, Cd, Cu, fluoride, Pb, Se | Rural |
| D. Material handling | - | 1,235 | As, Cd, Cu, fluoride, Pb, Se | Rural |
| XII. Primary zinc | | | | |
| A. Roasting | - | 34,187 | As, Cd, Cu, fluorides, Pb, Se, Zn | Urban, rural |
| B. Sintering | - | 14,044 | Cd, fluorides, Pb, Zn | - |
| C. Distillation | - | 4,676 | Cd, fluorides, Pb, Zn | |
| XIII. Primary lead | | | | |
| A. Sintering | - | 1,016 | As, Cd, fluorides, Pb, Se | - |
| B. Blast furnace | - | 275 | As, Cd, fluorides, Pb, Se | |
| XIV. Primary aluminum | | | | |
| A. Reduction cells | - | 16,230 | Fluorides (gas and solid) | Urban, rural |
| XV. Iron ore pellet plant | - | 18,200 | Fluorides | Rural |
| XVI. Asphalt roofing materials | - | 23,230 | POM | Urban |
| XVII. Secondary copper | - | 1,036 | Cd, Cu, Pb, Zn, POM | Urban |
| XVIII. Secondary lead | - | 2,020 | Pb | Urban |
| XIX. Secondary zinc | - | 3,840 | Zn | Urban |
| XX. Structural clay products | - | 9,720 | Fluorides | Urban, rural |

In developing a priority ranking of the sources presented in Table 11, equal weight was assigned to each of the adverse facets. Using this approach, the priority ranking in Table 12 was developed. Although quantitative detail is less than desired in Tables 11 and 12, the tables do suggest what should be the objective of initial efforts to control fine particulate emissions. The main thrust of initial efforts should be focused on the reduction of the mass of fine particulate emissions with emphasis placed on control of those sources which emit potentially hazardous materials and are located in or near urban areas. Potential approaches to the regulation of fine particle emissions are discussed in the next chapter.

Table 12. PRIORITY LIST FOR SOURCES OF FINE PARTICLE EMISSIONS

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Group I (High priority)

1. Stationary combustion (all fuel types)
   a. Electric utility
   b. Industrial
2. Iron and steel plants
   a. Open hearth furnaces
   b. BOF furnaces
   c. Electric arc furnaces
   d. Metallurgical coke ovens
3. Municipal incinerators
4. Ferroalloy plants
   a. Electric furnace
   b. Blast furnace
5. Primary nonferrous metallurgy
   a. Zinc roasting, sintering and distillation
   b. Copper roasting and converting
   c. Aluminum reduction cells

Group II (Medium priority)

1. Hot-mix asphalt plant
2. Iron foundry cupolas
3. Asphalt roofing materials
   a. Asphalt blowing
4. Secondary copper, lead and zinc

Group III (Low priority)

1. Iron ore pellet plants
2. Structural clay products
3. Cement and lime plants
4. Kraft pulp mills
5. Crushed stone

# SECTION VI
# APPROACHES FOR REGULATING FINE PARTICLE EMISSIONS

## INTRODUCTION

The goal(s) of the control program for fine particulates will be the main factor in the selection of approaches for regulating the emission of fine particulates. If the aerosol burden in the urban atmosphere is to be reduced, a premium must be placed on the collection of particles smaller than 5 µm. If improved visibility is the goal of fine particulate control programs, attention must be focused on particle collection in the 0.1-1.0 µm range. Concern for adverse health effects should direct attention to the control of the 0.01-7 µm size range, and to potentially hazardous constituents (e.g., lead, cadmium, vanadium, and particulate polycyclic organic matter) of the effluent stream.

Two approaches, distinguished by their initial focal point, can be used to regulate emissions of fine particulates from stationary sources:

1. Ambient air quality standards expressed in terms of fine particulates, and

2. Direct reduction of emissions from specific sources.

The ambient air quality approach requires as an initial step a statement specifying the desired objective in terms of atmospheric concentration, e.g., so many micrograms per cubic meter of total particulate plus a limitation on the contribution to total weight accounted for by particles of given diameter(s). The second step requires determination by measurement of existing ambient concentrations of particles of given diameter(s). From the information developed in these two steps, a ratio can be derived describing the fraction by which present emissions must be reduced to achieve the ambient standard. The final step requires development of data showing existing rates of emission from sources and the formulation of emission reduction plans derived by application of the ratio obtained in Step 3.

The second approach focuses attention on the direct reduction of emissions from specific sources, without initial recourse to ambient air quality. This approach is based on the premise that, to the extent feasible, fine particulates should be prevented from entering the atmosphere without initial consideration of the ambient air quality. Measurements of changes in ambient air quality before and after the initiation of control activities provide an indication of the overall effectiveness of the control effort.

Before an approach based on ambient air quality could be utilized effectively, data on (1) existing ambient air quality as a function of particle diameter(s) and (2) existing rates of emission must be available from numerous regions throughout the country. Acquisition of such a data base would require the expenditure of a great deal of time and money. A significant time lag would also occur before efforts to control fine particulate emissions could commence if this approach were selected.

If it were decided to initiate efforts to control fine particulate emissions in the near future, direct reduction of emissions from specific sources could be started immediately. Although the existing data base on emissions of fine particulates from stationary sources is lacking in detail and precision, it could be used to formulate initial emission reduction programs. As more and improved information on emission rates becomes available, the emission reduction programs could be refined.

The effectiveness of any program for the control of fine particulate emissions must ultimately be judged by improvements in ambient air quality. Because both atmospheric conversion processes (chemical and physical) and sedimentation contribute to the fine particulate burden in the atmosphere, it may be quite difficult to relate atmospheric fine particulate levels to control activities on specific sources. The City of Los Angeles is a good example of this situation. In Los Angeles about 35% of the ambient particulate burden is formed in the atmosphere from gaseous pollutants (see Table 13).[64] In cities like Los Angeles, a program based on ambient air quality might not be very effective. Atmospheric processes might also make interpretation of the overall effectiveness of direct regulation of sources difficult in some cases. For example, in Los Angeles reductions in emissions of fine particulates from stationary sources would not result in a proportionate decrease in ambient fine particulate concentration. While the assessment of the overall effectiveness of direct regulation of sources may be difficult in some cases, the total burden of

## Table 13. ESTIMATED CONCENTRATIONS OF LOS ANGELES AEROSOL PARTICLES BY SOURCE[64]

(Annual Average)

| Source | Mass Concentration ($\mu g/m^3$) | |
|---|---|---|
| Natural background | | |
| Primary . . . . . . . . . . . . . . . . . . . . . . . . . . | | 14-26 |
| Dust rise by wind | 8-20 | |
| Sea salt $Na^+$ | 3 | |
| Sea salt $Cl^-$ | 3 | |
| Spores, pollen, etc. | Unknown | |
| Secondary . . . . . . . . . . . . . . . . . . . . . . . . . | | 4- 7 |
| Vegetation (organic vapors) | 3- 6 | |
| Biological (soil bacterial action, decay of organics) -$NH_3$, $NO_x$, S . . . | 0.7 | |
| Man-made | | |
| Primary . . . . . . . . . . . . . . . . . . . . . . . . . . | | 36 |
| Motor vehicles | 15 | |
| Organic solvent usage | 6 | |
| Petroleum | 1.3 | |
| Aircraft | 4 | |
| Combustion of fuels | 5 | |
| Other | 5 | |
| Secondary . . . . . . . . . . . . . . . . . . . . . . . . . | | 39 |
| Reactive hydrocarbon vapors | 11 | |
| $NO_3$ | 13.5 | |
| $SO_4$ | 14.4 | |
| Total Accounted For | | 93-108 |
| Measured Total | | 119 |

fine particulates entering the atmosphere would nonetheless be reduced by direct limitation of source emissions. In the case of potentially hazardous pollutants, which in many instances are really fine particulates, direct regulation of source emissions is the only viable approach. The Environmental Protection Agency has already set a precedent in this area by adopting emission standards for sources of mercury, beryllium and asbestos. The preceding discussion indicates that direct reduction of fine particulates from specific sources is the most effective method to insure reduction of the fine particulate burden emanating from man's activity.

In the development of programs for the direct reduction of emissions from specific sources of fine particulates, a decision must be made regarding whether to limit regulation efforts to primary particulates or whether both primary and secondary particulates emitted from sources will be subjected to regulation. Primary particulates are defined as material that is emitted from the source or its exhaust stack in a particulate form. Secondary particulate is defined as particulate matter formed (primarily by physical processes, e.g., condensation) in the atmosphere from source effluents shortly after emission from the source or its exhaust stack. These secondary particulates are not the particulates formed in the atmosphere from gases and existing particles. As noted in Chapter 3, some of the potentially hazardous pollutants may be emitted from specific sources as a vapor which subsequently condenses into a fine particulate in the atmosphere shortly after exit from the stack or exhaust point. Although cause-effect relationships for health effects associated with fine particulate pollutants are not quantitative, efforts to regulate fine particle emissions from stationary sources should be focused on minimizing the impact of fine particulate pollutants on human health. In general, this stipulation requires control of both primary and secondary particulates in the nominal size range of 0.01-5 μm.

The preceding comments serve to highlight some of the more important facts that must be considered in the development of effective control strategies for fine particulate emissions. Various approaches that might be used to regulate fine particulate emissions from stationary sources are discussed in the following sections of this chapter.

## METHODS FOR REGULATING FINE PARTICLE EMISSIONS

Because our understanding of the importance of fine particulate pollution to man's health and welfare is in its infancy, it seems prudent to consider a long-range regulation strategy based on the adoption and implementation of progressively more stringent regulations for the control of fine particulates. Each step toward more effective control of fine particulates would be based upon improved knowledge of (1) the effects of fine particulates on human health and welfare; (2) the technical and economic impact of the more stringent regulations; and (3) the benefits that would accrue to society from a further decrease in fine particulate pollution. Three time-frames that might be considered are:

1. Regulations that can be proposed and implemented in the near term (i.e., by 1975).

2. Regulations that can be proposed and implemented in an intermediate term (i.e., 1980-1985).

3. Regulations that can be proposed and implemented in the long term (i.e., by 1990).

Any method(s) selected for regulation of fine particulate emissions should be chosen to facilitate interfacing with existing strategies for the control of particulate pollutants. Since the effluent or emission standard is the backbone of current control programs, interfacing fine particle control efforts with existing programs would be facilitated by the use of emission standards as the main tool in the regulation of fine particulates. Other methods that could be used to prevent or regulate fine particle emissions include: (1) tax incentives; (2) process modifications; (3) substitution of ingredients or fuels; and (4) cessation of processing operations that emit fine particles. The last alternative is deemed untenable except in very special situations. Each of the other methods is a viable approach, although methods (2) and (3) are probably limited in the extent to which they can be used.

As noted in the preceding paragraphs, a precedent exists for utilizing emission standards as the main method for control of fine particulate emissions in the near term. Current programs for the control of particulate pollutants are built around emission standards, and minimum disruption in control agency activities would occur if similar methods were used for fine particulates. In the intermediate to long term, the unavailability of sufficiently high efficiency control equipment and adequate source compliance monitoring methods and/or instrumentation may limit the utility of emission standards, especially if fine particulate or specific components of fine particulate emissions must be controlled to a very high degree. Alternative regulatory strategies based on tax incentives, might be attractive in that event. Both positive[*] and negative[+] tax incentives could be considered, but the negative incentive in the form of an effluent tax is deemed more beneficial. The negative tax incentive, in the form of an emission or effluent tax, has attracted some support recently. The proposal for charges on sulfur dioxide emissions is an example.

## BASIS FOR EMISSION STANDARDS FOR FINE PARTICULATES

Emission standards for the control of fine particulates could be based on concentration of fine particulates in an effluent stream, collection efficiency of control equipment, plume opacity, mass-emission rate of fine particulates, and hazard potential of the particulates.

Standards based only on concentration of fine particulates in an effluent stream have a very significant deficiency; namely, they generally ignore the volume of gas emitted from a source. As a consequence, such standards would not control the total fine particulate pollutant discharge from a specific source unless they incorporated considerations of the size of sources along with a specification of the allowable fine particulate grain loading. An extensive data base relating particle size and grain loading to source size would need to be developed before this approach could be implemented.

The requirement of a specific collection efficiency in given particle size ranges, and the installation of the best installed control[+] device[++] on all sources in a specific category, are two examples of standards based on the collection efficiency of control equipment. Combined with a limitation on the total mass emission for a specific source, such an approach has merit. An emission standard combining those facets would limit both the total mass emitted as well as the mass in the fine particle size range. The lack of reliable data on the efficiency of control equipment as a function of particle size (i.e., fractional efficiency) might make it difficult to utilize the approach of designating the collection efficiency in specific size ranges. The alternative of requiring the installation of the best installed control on sources is somewhat analogous to extending new source performance standards to all sources in a specific category. A standard utilizing this approach might be expressed in terms of a maximum allowable total mass emission and a minimum allowable control device collection efficiency. Since a standard based on the specification of control device collection efficiency requires the same degree of control for large and small sources, a distinct possibility of undue regulation of small sources and insufficient regulation of large sources might occur with this type of regulation. However, with some adjustment to account for plant size, a standard based on the installation of the best installed control devices on all sources in a specific category is a potential vehicle for the regulation of fine particulate emissions. Determination of the effectiveness of such an emission standard would require extensive source testing.

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[*] Positive tax incentives--include not only direct payments or subsidies but also reductions in property taxes, accelerated depreciation and tax credits.

[+] Negative tax incentives--this category includes effluent charges or fees for the discharge of specific amounts of pollutants or other taxes on specific sources of pollution.

[++] Best installed control device is not necessarily the highest efficiency device available, but rather the best that is generally being installed at present time.

Because the opacity of a plume is a function of the size of entrained particulate matter, and particles in the size range 0.1-1.0 μm have the dominant effect on plume opacity characteristics, plume opacity regulations provide a vehicle to control fine particle emissions. Since opacity regulations are currently utilized by many regulatory agencies, no problems would be encountered in interfacing with current particulate control programs. The trend in opacity regulations is toward 20% opacity[65]--a regulation of 10% or 5% opacity could be used as a more stringent opacity regulation.

Mass-emission regulations provide a direct approach to the control of fine particle emissions. Regulations based on mass emissions could be formulated to control the quantity of material emitted in specific size ranges, and could be based on either process-weight rate or on potential-emission rate. Process weight regulations specify the maximum allowable discharge rates for particulates in pounds per hour in relation to the process weight in pounds per hour. Process weight is defined as the total weight of all materials introduced into a process, except liquid or gaseous fuels or combustion air, divided by the time in hours to complete the process. Process-weight regulations generally are formulated so that the absolute allowable discharge increases with increasing process weight. However, the percentage of process material which is permitted to be discharged decreases as the process weight increases.

Emission standards can also be formulated to specify maximum allowable emission rates (lb/hr) of fine particulate as a function of the fine particulate emission potential of the source (lb/hr). The potential emission rate is defined as the total weight rate at which fine particulate matter is, or in the absence of an air-cleaning device would be, emitted from an air contamination source when such source is operated at its maximum rated capacity.

The potential-emission rate concept appears to be a direct and useful basis for formulating standards to control the emission of fine particulate pollutants. This approach should result in a better understanding of the main parameters that influence fine particulate emissions from specific sources. Once the potential rate of emission of fine particulates is established for various sources, allowable emission rates can be set to tailor the control of fine particulate emissions to any desired level.

Our analysis has indicated that the most promising bases for emission standards for fine particulates are: (1) plume opacity; (2) minimum collection efficiency for fine particulates; and (3) potential emission rate concept. Each of these is discussed in more detail in the following sections.

## Plume Opacity Standards

The opacity of a particulate emission depends on the mass concentration of the particles comprising the plume, their size distribution and physical properties such as density and refractive index. Other parameters such as plume width and wavelength of incident light are also important in determining opacity. It is the dependence of plume opacity on mass concentration and particle size, especially in the 0.1-1.0 μm size range, which makes it possible to control the emission of fine particulates by controlling the opacity of the exhaust plume.

As previously noted, Ref. 65 indicates that the trend in plume opacity regulations is toward 20% opacity. Standards based on 10% or 5% (i.e., essentially no visible emission) could be used to reduce the emission of fine particulates. The use of opacity regulations to control fine particulate emissions involves some subtleties, and care will have to be taken in order to develop useful regulatory programs. A brief review of the mathematical expressions used to define plume opacity is given in Appendix C, and this review delineates some of the important implications regarding the use of opacity regulations.

Because of the strong dependence of plume opacity on factors such as the optical properties of the particulate matter, each source under scrutiny must be described in detail before plume opacity has practical meaning. This fact is illustrated by Figure 9.[66/] Figure 9 presents plume opacity as a function of particle diameter and dust loading for particles with a density of 2 $g/cm^3$ and for 5 ft dia. stacks with exit temperatures of 300°F.

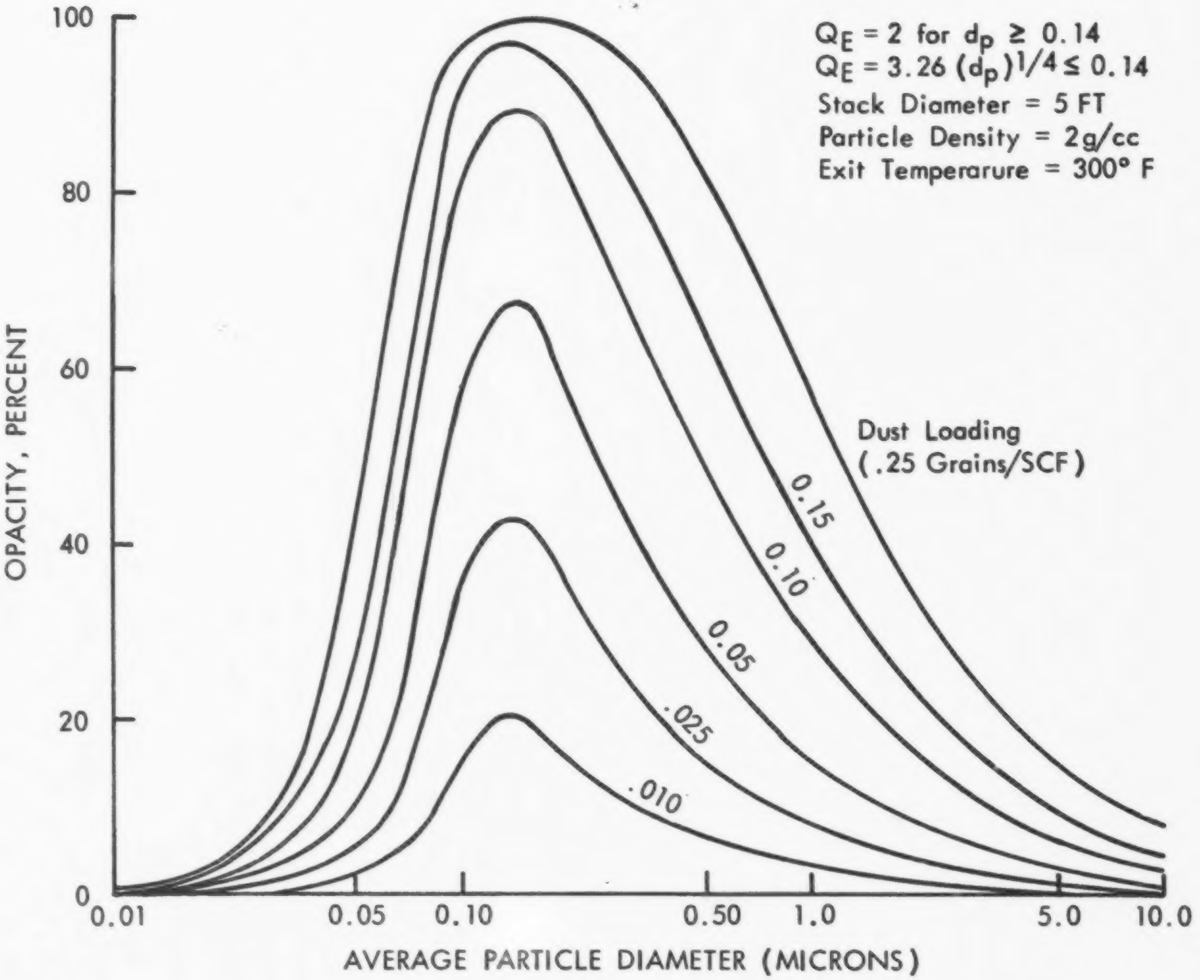

Figure 9. Plume opacity as a function of particle[66/] diameter and dust loading

A fairly stringent standard for grain loading is 0.05 grain/scf. From Figure 9 it is noted that if the particulates are large enough that the average is greater than 5 μm or so, an opacity requirement of 20% is not strict compared to the 0.05 grain loading requirement. If the average particle diameter is 1/2 μm or so, a 20% opacity requirement would be more strict. In order to accomplish the desired control of fine particulates via the regulation of plume opacity, it may be necessary to develop regulations that require a different plume opacity for various sources.

More refined information on particulate properties will be required in order to develop effective strategies for control of fine particulates via opacity regulations. A more comprehensive data base will also be needed to develop acceptable source compliance monitoring techniques. Requirements for source monitoring will be discussed further in Chapter 5.

## Minimum Collection Efficiency for Fine Particulates

An emission standard which designates a minimum collection efficiency for fine particulates in combination with a limitation of total emission as a function of source size could serve as a vehicle for the control of fine particulates. A collection efficiency standard alone is not a viable approach because it would not directly limit the total mass of fine particle emissions. The minimum collection efficiency could be achieved by (1) specifying minimum collection efficiency in designated particle size ranges, or (2) requiring the installation of the best installed control device on all sources in a specific category.

An emission standard incorporating minimum control efficiency in specific particle size ranges could be designed to provide not only control of fine particulates in general but also control of specific chemical constituents of the fine particulate stream. The Bay Area Air Pollution Control District (San Francisco, California) has entertained discussions regarding the feasibility of modification of their Regulation 2 regarding particulate emissions to incorporate minimum collection efficiency in designated particle size ranges. The suggested modifications would supplement Regulation 2 with a new type of performance standard based on minimum control efficiency in particle size ranges as follows:[67/]

| Efficiency (weight %) | Particle Size Range |
|---|---|
| 99 | 10 μm or larger |
| 97 | 3-10 μm |
| 92 | 0-3 μm |

The above performance standard is but one of an almost unlimited number of standards that could be formulated using the basic concept of designated efficiencies as a function of particle size. Tailoring of a regulation for a specific source category is an obvious possibility with this type of standard. A considerable amount of data on particle size and other effluent characteristics would have to be developed to show what collection efficiencies are practical in various size ranges below about 2 µm.

An emission standard utilizing the requirement of installation of the best installed control technology on all sources in a specific category would in effect specify the minimum allowable collection efficiency on a total mass basis. Since the collection efficiency on a total mass basis is the summation of efficiencies for all particle sizes, control of particles in specific size ranges would be achieved by this approach. In terms of existing technology for control systems, this approach would also represent the current practical limit of an emission standard based on designation of minimum control efficiency in specific particle size ranges. Determination of the effectiveness of a standard requiring the installation of the best installed control technology would require extensive source-testing in order to develop accurate data on control device fractional efficiencies for a spectrum of sources of fine particulate pollutants.

## Mass-Emission Regulations

The use of emission standards which limit the quantity of fine particulate emitted from specific sources is the most direct approach to regulating fine particulate emissions. Process-weight rate, potential emission rate, or parameters that reflect source size (e.g., heat input in $10^6$ Btu/hr) could form the basis for this type of regulation. In the latter category, the New Mexico Environmental Improvement Board has taken a pioneering role and has adopted a regulation for coal-burning equipment that is aimed at regulating fine particulate emissions from that type of source. The New Mexico regulation reads as follows:

> "After December 31, 1974, no person owning or operating coal-burning equipment shall permit, cause, suffer, or allow:
>
> "1. Particulate matter emissions to the atmosphere in excess of 0.05 lb/million British thermal units of heat input; or
>
> "2. Fine particulate matter emissions of less than 2 µm equivalent aerodynamic diameter and unit density to the atmosphere in excess of 0.02 lb/million British thermal units of heat input.

> "Fine particulate matter emissions for this regulation shall be collected and measured at stack conditions and in such a manner that no condensation of gaseous material is included with the sample."

Process-weight rate regulations are currently used as an integral part of many air pollution control programs. Historically, process-weight rate regulations have been developed from data obtained from well-controlled and well-operated plants. Source testing data acquired from such plants form the basis for determining the degree of control that is technically and economically feasible. To utilize this type of regulation to reduce the emission of fine particulates, it will be necessary to have accurate data regarding:

1. Quantity of particulate emitted from various well-controlled sources;

2. Particle size distribution of the particulate emitted; and

3. Fractional efficiency characteristics of various control devices.

Currently available data in the above areas are inadequate for the formulation of effective emission standards.

With regard to the regulation of fine particulate emissions, process-weight rate may not be a good basis for an emissions standard because the quantity of fine particulate emitted from a source may not be directly related to process weight. Available data suggest that factors such as nature of ingredients, processing conditions, and equipment and hooding and ducting configurations have a much stronger influence on fine particulate emissions than does the process-weight.

The concept of potential-emission rate offers an alternate basis for emission standards to regulate fine particulate pollution. Regulations based on this concept establish emission limits which vary with the pollution potential of the source, e.g., limitation of mass rate of emissions in lb/hr as a function of potential-emission rate, also lb/hr. This type of regulation appears to be adaptable to sources of fine particulate pollutants. Three variations of the potential emission rate concept are depicted in Figure 10.

1. Specification of the minimum efficiency (on a mass basis) of collection of the potential emission of less than 2 μm particulates. Curves A, B, C, and D, in Figure 10, represent four of the many collection efficiency regulations that could be utilized. Curve C, 99 wt % collection

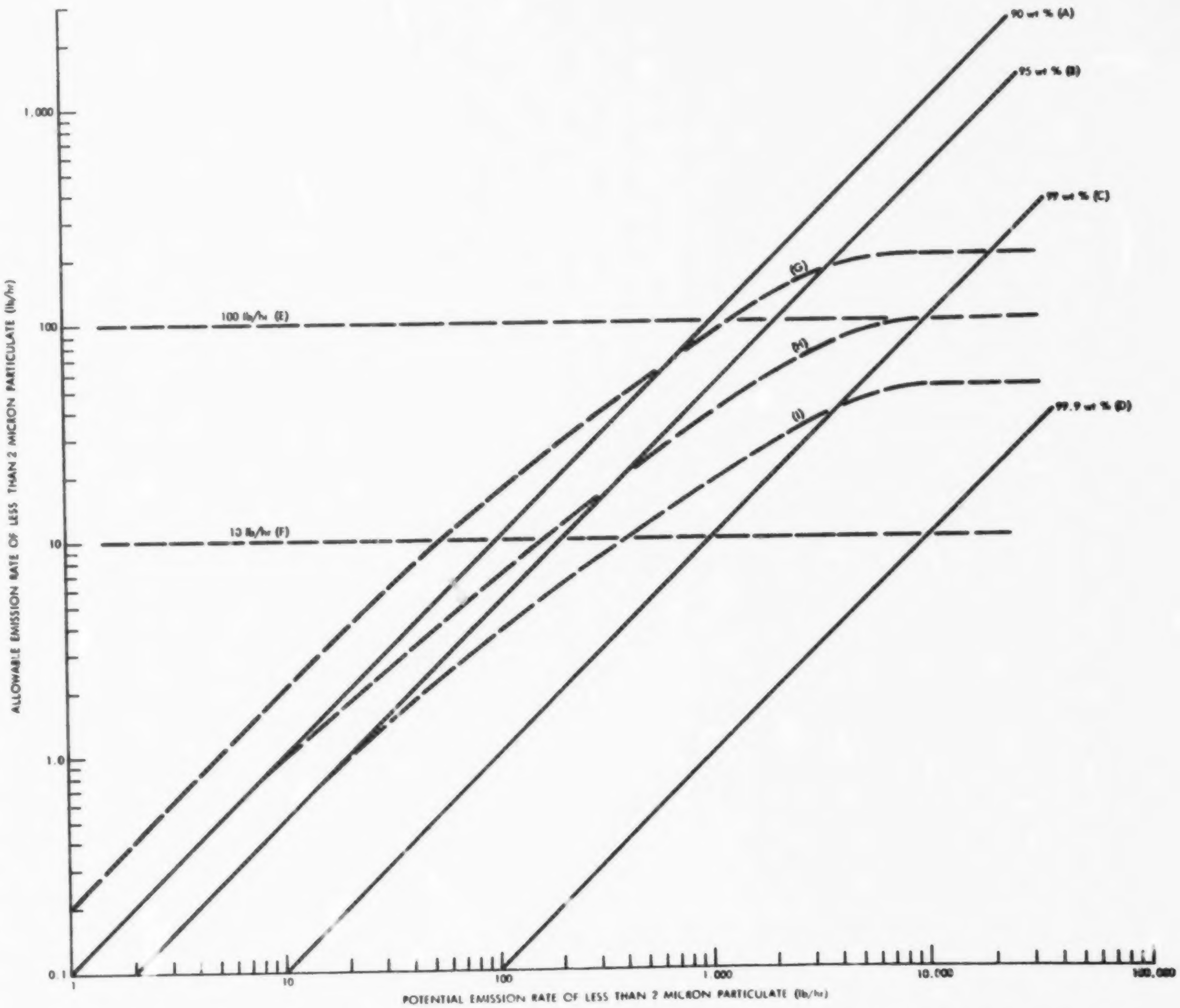

Figure 10. Representative emission standards based on potential emission rate

efficiency for less than 2 µm particulate, represents the probable upper limit of efficiency for currently available control equipment. This variation actually corresponds to the minimum collection efficiency concept previously discussed with potential-emission rate as the basis.

2. Direct limitation of the quantity (i.e., pounds per hour) of less than 2 µm particulate that can be emitted from any source without consideration of the emission potential of any specific source. Curves E (100 lb/hr allowable emission rate) and F (10 lb/hr allowable emission rate) are representative of this type of regulation.

3. Regulations based on a sliding scale of allowable emission as a function of potential emission. The sliding scale is adjusted to force sources with large emission potential to use higher efficiency collection methods than sources with smaller emission potentials. Curves G, H, and I are representative of this form of regulation.

Potential-emission rates of fine particulates for specific sources could be determined by sampling the uncontrolled effluent gases, and source compliance could be determined by measuring control equipment efficiency. Alternatively potential-emission rates could be assigned to sources through use of pre-established emission factors for fine particulates. Because an emission factor ideally represents the average measured emission rate from a number of similar installations, the use of such factors is a logical and equitable substitute for determining potential-emission rates for each individual source. Since currently available data are inadequate, an extensive data base would need to be developed before this concept could be implemented.

## EMISSION STANDARDS SELECTED FOR EVALUATION

Our analysis of the alternative routes for emission standards for fine particulates led to the following observations:

1. The use of standards involving plume opacity is the most practical means for controlling fine particulate emissions in the near term. Standards based on plume opacity would require the least amount of additional data acquisition and they would readily interface with existing air pollution control programs.

2. An emission standard based on the requirement of the installation of the best installed technology on all sources in a specific category

could be implemented in the intermediate term. A standard of this type would represent the attainment of the current practical limit of control equipment performance.

3. A mass emission regulation based on the potential emission rate concept is a very attractive approach for the long term. A regulation of this type could be tailored to the control of specific sources or specific pollutants.

The technical and economic implications of these types of emission standards are analyzed in Chapters 5, 6, and 7.

# SECTION VII

# TECHNOLOGICAL IMPLICATIONS OF FINE PARTICLE EMISSIONS REGULATIONS

## INTRODUCTION

Implementation of any regulation(s) for the control of fine particulate pollutants from stationary sources requires the availability of technology in two distinct areas:

1. Control equipment, and

2. Compliance testing and monitoring.

In selecting a regulation for the control of fine particulates, it is necessary that the regulation be realistic in the sense that control technology must be available to permit the requisite collection of fine particulates. In addition, methods must be available to ascertain whether or not specific sources are in compliance with the regulation(s).

## REQUIREMENTS FOR CONTROL EQUIPMENT EFFICIENCY

Regulations to control the emission of fine particulate pollutants will require the use of high-efficiency control equipment. Depending upon the type of regulation adopted, the performance capability of control systems may be stretched to the limit of existing technology. An analysis of the collection efficiency required to meet stringent plume opacity regulations provides an indication of the level of performance that will probably be required.

The translation of an opacity regulation into terms of the overall mass efficiency required of control equipment necessitates the use of a relationship between plume opacity and various particulate and source characteristics. Ensor and Pilat have developed a procedure to calculate plume opacity from plume diameter, particle size distribution, particle mass concentration, average particle density, and particle refractive index.[68] (Also see Appendix C.) Equation (4) presents the relationship developed by these authors to calculate the expected mass concentration for various values of plume transmittance (or opacity), average particle density, and plume diameter.

$$W = -K\ \rho/L\ \ln\ (I/I_o) \qquad (4)$$

In Eq. (4),

$W$ = Total particulate mass concentration (i.e., grain loading) at stack conditions

$\rho$ = Average particle density

$L$ = Diameter of plume

$I/I_o$ = Light transmittance

$$K = \frac{\text{Specific particulate volume}}{\text{Extinction coefficient}}$$

The assumptions and simplifications involved in the derivation of Eq. (4) are discussed in Ref. 68. Although Eq. (4) is not exact, it can be utilized to determine, with sufficient accuracy for the present purpose, the total particulate mass concentration corresponding to various combinations of $\rho$, L, K, and $I/I_o$ values.

The parameter K is a function of the particle size distribution, the refractive index of the particulate, and the wavelength of incident light. Reference 67 presents graphs of K vs the geometric mass mean particle radius with the geometric standard deviation of the particle size distribution and the refractive index of the particles as parameters. A wavelength of light of 0.55 μ was used as an average for visible light. This is approximately the wavelength of maximum sensitivity for the human eye. Equation (4), combined with the graphs for the parameter K, and information on effluent properties from specific sources of particulate pollution presented in Ref. 62, was used to develop the control efficiency vs plume opacity data presented in Table 14.

The selected values of plume opacity (20%, 10% and 5%) correspond to Ringlemann No. 1, No. 1/2, and "no visible emissions." The total mass efficiency required for a control device to reduce plume opacity to these

Table 14. CONTROL DEVICE EFFICIENCY REQUIRED TO ACHIEVE VARIOUS PLUME OPACITY LEVELS

| Source | K ($cm^3/m^2$) | $\rho$ ($g/cm^3$) | L (meters) | Plume Opacity ($I/I_o$, %) | Grain Loading at Inlet to Control Devices (gr/scf) Low | Grain Loading at Inlet to Control Devices (gr/scf) Average | Grain Loading at Inlet to Control Devices (gr/scf) High | W Grain Loading at Exit of Control Device (gr/scf) | Total Mass Efficiency Required for Control Device (%) Low Inlet | Total Mass Efficiency Required for Control Device (%) Average Inlet | Total Mass Efficiency Required for Control Device (%) High Inlet |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal-fired power plant | 0.64 | 2.[illegible] | 2 | 20 | 1.0 | 3.0 | 6.0 | 0.09 | 91.0 | 97.0 | 98.5 |
| | | | | 10 | | | | 0.037 | 96.3 | 98.8 | 99.3 |
| | | | | 5 | | | | 0.02 | 98.0 | 99.5 | 99.7 |
| | | | 5 | 20 | | | | 0.036 | 96.4 | 98.8 | 99.4 |
| | | | | 10 | | | | 0.017 | 98.3 | 99.4 | 99.7 |
| | | | | 5 | | | | 0.008 | 99.2 | 99.7 | 99.9 |
| | | | 10 | 20 | | | | 0.018 | 98.2 | 99.5 | 99.7 |
| | | | | 10 | | | | 0.0085 | 99.1 | 99.7 | 99.8 |
| | | | | 5 | | | | 0.004 | 99.6 | 99.9 | 99.9 |
| Basic-oxygen furnace | 0.20 | 3.5 | 2 | 20 | 2.0 | 5.0 | 10.0 | 0.07 | 96.5 | 98.6 | 99.3 |
| | | | | 10 | | | | 0.033 | 98.3 | 99.3 | 99.7 |
| | | | | 5 | | | | 0.016 | 99.2 | 99.7 | 99.8 |
| | | | 5 | | | | | 0.028 | 98.6 | 99.4 | 99.7 |
| | | | | | | | | 0.013 | 99.3 | 99.7 | 99.9 |
| | | | | | | | | 0.006 | 99.7 | 99.9 | 99.94 |
| | | | 10 | 20 | | | | 0.014 | 99.3 | 99.7 | 99.9 |
| | | | | 10 | | | | 0.007 | 99.7 | 99.9 | 99.9 |
| | | | | 5 | | | | 0.003 | 99.9 | 99.94 | 99.97 |
| Cement plant--rotary kiln | 1.1 | 3.0 | 2 | 20 | 1.0 | 6.4 | 17.0 | 0.30 | 70.0 | 95.5 | 98.2 |
| | | | | 10 | | | | 0.15 | 85.0 | 97.8 | 99.2 |
| | | | | 5 | | | | 0.069 | 93.0 | 99.0 | 99.8 |
| | | | 5 | 20 | | | | 0.12 | 88.0 | 98.1 | 99.0 |
| | | | | 10 | | | | 0.06 | 94.0 | 99.0 | 99.7 |
| | | | | 5 | | | | 0.0275 | 97.0 | 99.6 | 99.9 |
| | | | 10 | 20 | | | | 0.06 | 94.0 | 99.1 | 99.7 |
| | | | | 10 | | | | 0.03 | 97.0 | 99.5 | 99.9 |
| | | | | 5 | | | | 0.0138 | 98.7 | 99.8 | 99.95 |
| Asphalt plant--rotary dryer | 10 | 2.6 | 2 | 20 | 10.0 | 30.0 | 70.0 | 1.70 | 83.0 | 94.3 | 97.6 |
| | | | | 10 | | | | 0.81 | 91.9 | 97.3 | 98.8 |
| | | | | 5 | | | | 0.39 | 96.1 | 98.7 | 99.4 |
| | | | 5 | 20 | | | | 0.68 | 93.2 | 97.7 | 99.0 |
| | | | | 10 | | | | 0.32 | 96.8 | 98.9 | 99.5 |
| | | | | 5 | | | | 0.16 | 98.4 | 99.5 | 99.8 |
| | | | 10 | 20 | | | | 0.34 | 96.6 | 98.9 | 99.5 |
| | | | | 10 | | | | 0.162 | 98.4 | 99.5 | 99.8 |
| | | | | 5 | | | | 0.078 | 99.2 | 99.7 | 99.9 |

values is shown in Table 14 for various values of the inlet grain loading to the control device and plume diameter. The range of inlet grain loadings for specific uncontrolled sources was taken from data in Ref. 68. The plume diameters were arbitrarily chosen to represent a spectrum of diameters.

Inspection of the data in Table 14 indicates that a plume opacity limitation of 20% (Ringlemann No. 1), which is the current trend in opacity regulations, would require an efficiency ranging from 94-99.5% on a total mass basis for sources with an average inlet grain loading. That degree of collection efficiency represents control equipment of medium to high efficiency. A plume opacity limitation of 10% would require a collection efficiency of 97-99.9% for sources with an average inlet grain loading. If a 5% plume opacity limitation were imposed, sources with an average inlet grain loading would be required to control emissions to a level of 99-99.9% efficiency.

Compliance with a 10% or 5% plume opacity standard would require the use of high-efficiency control systems which approach the limits of current technology. The capability of current control equipment obviously places a constraint on the degree of reduction of fine particulate emissions that can be achieved by any type of emission standard in the near term. The status of existing and emerging control technology for fine particulates is discussed in more detail in the following sections.

## CAPABILITY OF CONTROL TECHNOLOGY

The current capability of control equipment to collect fine particulates is of immediate concern, while the potential of new control methods or emerging technology is of importance with regard to regulations that might be devised for the intermediate to long term. Appendix A presents a detailed review of existing and emerging control technology, and only the major points of the review are presented in the following sections.

### Capability of Existing Control Equipment

Four basic types of control devices (electrostatic precipitators, wet scrubbers, fabric filters, and afterburners) can currently be used to collect fine particulates. Afterburners have limited utility since the particulate must be combustible in order to employ this type of control device. The fabric filter is usually considered to offer the highest collection efficiency; for the greatest number of sources. However, it is not applicable to some sources of particulate pollutants because of the nature of the particulate, or the high cost involved in conditioning the gas stream.

The ability of control devices to collect particulate matter, and especially the fine particles, is commonly expressed in terms of their fractional efficiency. MRI has accumulated much of the available data on the fractional efficiency of control devices. Analysis of these data (as explained in Appendix A) has resulted in the generalized fractional efficiency graph shown in Figure 11. The curves shown in Figure 11 indicate the efficiencies that may be expected for the basic types of control devices as a function of particle size. There are, however, several variations in design of those control devices which is one reason for the broad ranges in efficiency and may be the reason why reported efficiencies for specific devices are not necessarily in agreement with these curves.

A comparison of the efficiency data presented in Figure 11 and the total mass efficiency required for control devices to meet stringent opacity regulations (10% or 5% opacity, Table 14) shows that only high-efficiency electrostatic precipitators, Venturi scrubbers or fabric filters are capable of meeting the opacity standards.

Achievement of a significant reduction in fine particulate emissions will require not only the use of high-efficiency control equipment, but also improvements in the reliability of control equipment. It is often assumed that control equipment is in operation 100% of the time that a source is operating. This is seldom the case, but data are generally not available on control equipment operational availability. An indication of the potential error in this type of assumption is provided by the results of a survey reported in Ref. 69. In Ref. 69, Greco and Wynot report the results of a study dealing with the performance and availability of electrostatic precipitators of 16 different design types serving 51 power generating units of TVA. The overall weighted average availability was reported to be 92.6% for a 1-year period of operation. For most industries the records of availability have not been reported.

The availability factor assumes considerable importance in the control of fine particulate pollutants. For example, an electrostatic precipitator of 99.5% overall mass efficiency which operates only 92.6% of the time a source operates is really equivalent to a net efficiency of 92.1%--a reduction of ~ 7.5% in actual collection efficiency. Reliability will obviously have to be improved to insure maximum equipment availability if efforts to control fine particulates are to be successful. More comprehensive maintenance programs for control equipment will undoubtedly be required.

Another area in which improvements will be necessary in order to achieve control of fine particulates is the capture efficiency of hooding systems that are associated with many installations of control devices. Capture

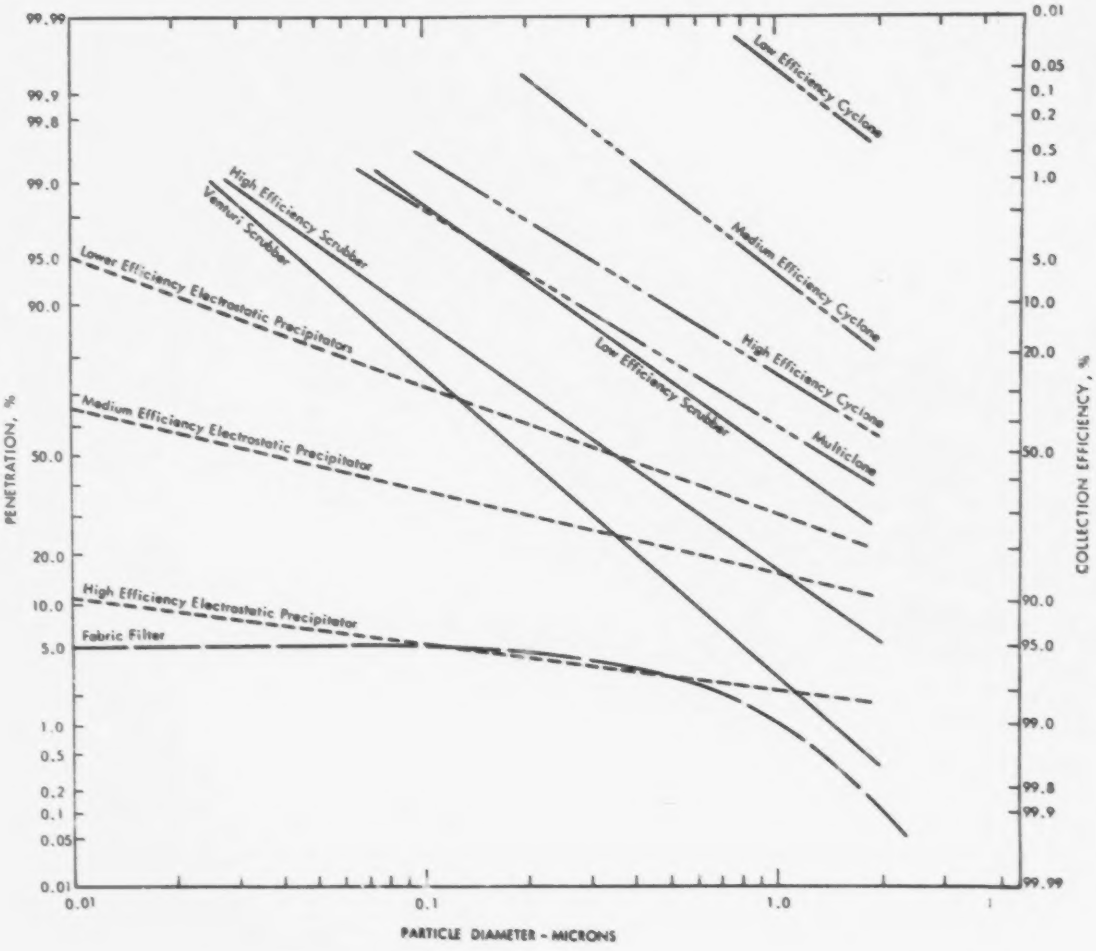

Figure 11. Extrapolated fractional efficiency of control devices

efficiency of hooding systems that are necessary for many sources such as metallurgical furnaces is frequently estimated to be less than 95%. If the control device efficiency is in excess of 99%, the particulate matter which escapes the hooding system becomes very significant.

The preceding discussion serves to emphasize that the control of fine particulates will require improvements in all phases of the technology. The major obstacle that will impede control efforts is the inherent limitations in ability of existing control equipment to collect submicron particles. Control technology, involving either improved control devices or particle conditioning processes, will need to be developed if we are to achieve a significant reduction in the emission of fine particulates from stationary sources. Recent work on new control technology is reviewed in the next section.

## Emerging and New Control Technology

There are several avenues that might lead to improved control of fine particulates: (1) development of new or novel particulate control devices; (2) augumentation of commonly used collection mechanisms by additional forces which do not approach zero in the $\leq$ 2 μm size range; and (3) utilization of particle conditioning or agglomeration techniques. The current status of technology in each of these categories is reviewed briefly in the following sections.

New or Novel Control Devices - A variety of devices which are claimed to have high collection efficiencies in the fine particle range have been reported in the technical and patent literature.[70,71] However, for most of these devices the supporting data for the claims are often meager, unavailable, or inconclusive. Additional testing programs will be required to determine the capability of these devices.

ADTEC system - One of the more promising new control devices is the ADTEC system. The ADTEC system is a wet scrubbing system that operates on the conventional Venturi collection mechanism of inertial impaction, but establishes the requisite particle-droplet differential velocity by utilizing waste process heat rather than external energy. On the basis of currently available information, this system appears to offer significant improvement in the collection of fine particles, at modest energy consumption rates, where a waste gas is available which contains a sufficient amount of thermal energy.[72,73]

Condensation scrubbers - Control devices utilizing steam condensation also appear to offer promise for improved collection of fine particulates. The main areas for utilization of steam condensation appear to be (1) in a particle conditioning device, and (2) in conjunction with various types of wet scrubbers. In the former category, a wide variety of condensation chambers might be designed to achieve growth of particles prior to introduction into a collection device.

Some existing types of wet scrubbers utilize, to some extent, condensation scrubbing mechanisms and particle growth by steam condensation. In a Venturi scrubber, for instance, if the aerosol is saturated in the pressure zone in the Venturi throat, the subsequent expansion (which is sudden and therefore approximately adiabatic), will cool the aerosol and cause condensation. The water tends to condense on the particles and the grown particles are more readily collected by impaction with the water drop spray. If the water drops are colder than the gas, the sweep mechanisms (i.e., diffusiophoresis and thermophoresis) may also cause the particles to move toward the water drops.

The main emission sources where the use of condensation mechanisms for fine particulate removal appear economically attractive are sources that have wet or saturated gas streams at temperatures on the order of 125°-175°F or sources with a waste heat stream in which the gas can be saturated down to 125°-175°F. Sieve-plate scrubbers may be an attractive configuration that would lend itself to maximization of condensation effects by utilizing combinations of cold and hot water plates.

Direct steam injection appears to be too expensive if the steam must be purchased. If a waste heat stream is available, steam generation from the waste heat might permit use of a control device employing direct steam injection.

Charged droplet scrubbers - The use of charged drops to agglomerate fine particulates has some potential for transition to commercial equipment. However, it appears that there is little reason to expect that systems based on charged drops will represent a breakthrough for collecting submicron particles. Devices utilizing charged drops may match electrostatic precipitators in performance and may offer advantages in volume savings over a conventional electrostatic precipitator. Also, charged drop scrubbers may be quite attractive for use on sources that emit corrosive and high-moisture content pollutant streams.

Augmentation of Collection Mechanisms - A potentially fruitful avenue to pursue in order to improve the collection of fine particulates is to augment commonly used collection mechanisms (e.g., inertia, impaction, interception) by forces which do not approach zero in the fine particle size range. Figure 12 presents the ratio of several forces acting on an aerosol

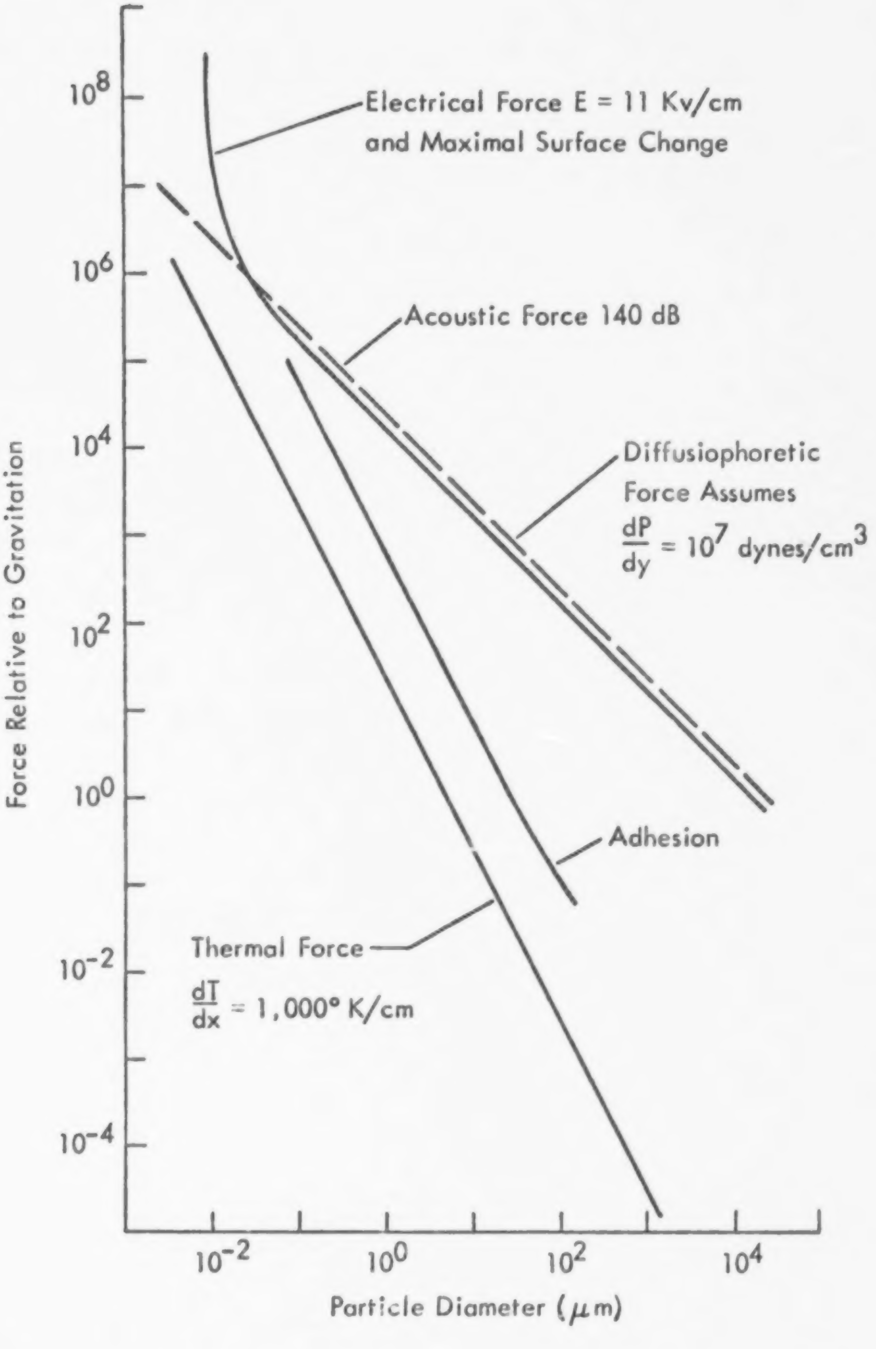

Figure 12. Forces operating on aerosol particles

particle to the weight of the particle (gravitational force) for particles from 0.01-$10^4$ μm in size. For particles < 1 μm the forces shown in Figure 12 are many times greater than gravitational forces. Thermal, diffusiophoretic, electrical and other forces shown in Figure 12 might be used advantageously for cleaning industrial gas streams containing fine particulates if devices can be designed and operated with reasonable energy requirements.

Agglomeration of Particles - The agglomeration or coagulation of particulates could be used as a step in a sequence of operations aimed at controlling the emission of fine particles. If sufficiently large particles can be produced, it may be possible to use conventional low-cost techniques as the final collection step. Only sonic agglomeration and the agglomeration of charged particles appear attractive.

Coagulation by a sonic field has as its principal advantages its applicability to any aerosol, including those comprised of submicron particles. The principal disadvantage of sonic coagulation is its relatively high energy requirements. A second major disadvantage is the low efficiency of acoustic coagulators and their inability to handle highly dispersed suspensions. Even with long residence times, sonic precipitators which incorporate inertial separators, cannot treat suspensions having particle loadings of < 0.5-1.0 grains/$ft^3$. It is therefore necessary to augment highly dispersed suspensions with a water mist or other particles to increase the particle loading and obtain satisfactory separation.

One method of increasing the rate of agglomeration of fine particulates is to add a bipolar charge, either with or without an externally imposed field. To a limited degree, this occurs in a standard electrostatic precipitator but not sufficiently to permit efficient collection of fine particulates. With proper conditions the large electrostatic forces between particulates can produce a large increase in the rate of agglomeration of submicron particulates.

The limited theoretical and experimental evidence available indicates that fine particulates can be coagulated with water mists in a bipolarly charged mixture on a practical scale. The resulting agglomerates can then be precipitated in either a conventional or space-charge electrostatic precipitator.

## SUMMARY OF STATUS OF CONTROL TECHNOLOGY

The only conventional control devices capable of significant collection of fine particulates are high-efficiency electrostatic precipitators, Venturi scrubbers and fabric filters. Existing data, as well as theory, on fine particulate collection efficiency (both on a mass and number basis) of conventional equipment indicate that inefficiency in the fine particulate range is an inherent characteristic of the equipment. Therefore, definite constraints will be imposed on the types of emission standards for fine particulates that can be implemented in the near term. The inherent limitations of existing control equipment may require that process modifications or other alternatives be used to meet near-term regulations.

Several physical phenomena exist that suggest possible avenues to improved fine particulate control. These include condensation scrubbing, sonic and charged droplet agglomeration and electrostatics. In general, their potential for enhancing the fine particulate collection efficiency for conventional control equipment as well as their potential for forming the basis for a unique collector cannot yet be fully assessed.

## REQUIREMENTS FOR COMPLIANCE TESTING AND MONITORING

Emission standards for fine particulates, if they are to be implemented and enforced, must specify some method(s) whereby the emission of fine particles can be measured or monitored. The emission standards selected for detailed study in this program involve regulation of two characteristics of the effluent stream from a source: (1) the opacity of the plume; and (2) the mass of fine particulates emitted. The method(s) used to determine compliance with these standards must, therefore, be able to accurately measure these characteristics. Since the ultimate success of efforts to control fine particulate emissions will be judged, at least in part, in terms of improvements in ambient air quality, the methods used to determine rates of emissions from sources should also be compatible with or relate to methods for determination of particulate concentrations in the ambient atmosphere.

A literature review was conducted as part of this program to identify measurement and monitoring methods that might be useful to determine compliance with emission regulations for fine particles. The search and subsequent evaluation activities were directed primarily to methods for determining plume opacity and manual or continuous methods for determining the mass concentration of particulates $< 3$ μm.

Several methods were identified and evaluated. A listing of the more promising methods is given in Table 15. General comments regarding some of the major advantages or disadvantages of each method are included in Table 15. In evaluating the methods, cost of the equipment was not an important criterion, but complexity of the methods was considered to be important. The primary consideration, however, was whether the method

Table 15. MEASUREMENT AND MONITORING METHODS FOR FINE PARTICULATES[a]

| A. Opacity methods | Comment |
|---|---|
| Visual | Precision not adequate for 5% and 10% opacity regulations. |
| Transmissometer | Recommended method, but not necessarily applicable for plumes containing condensed water vapor or for detached plumes. Source and detector must be purged with clean air. Calibration may be a problem. |
| **B. Mass emission methods** | **Comment** |
| Transmissometer | Correlation of transmissometer reading with concentration is possible, but dependent on properties of particulate matter. |
| Cutoff impactor and filter | Impactors subject to error due to pluggage, blowoff, moisture and overloading. |
| Cutoff cyclone and filter | Recommended manual method, but relies on single point anisokinetic sample. May require use of impingers if effluent contains condensible vapors. |
| Cutoff method and piezoelectric crystal | Crystal must capture particles and will probably require frequent cleaning or replacement. Not applicable for high particulate loadings. Might serve as a manual method to eliminate weighing of filters. |
| Cutoff cyclone and beta-tape | Offers best possibility of semicontinuous measurement. |

## Table 15. (Concluded) MEASUREMENT AND MONITORING METHODS FOR FINE PARTICULATES

| B. Mass emission methods (Concluded) | Comment |
|---|---|
| Sonic impingers | A simplified manual method, but collecting solution must be evaporated and weighed. Might possibly be fed continuously to Coulter counter. |
| Microscopy | An accurate method of counting and sizing particles, but method is tedious and expensive and not amenable to continuous monitoring. |
| Light scattering | Most methods are rather complex. They indicate number concentration rather than mass concentration. |
| Electric mobility analyzer (Whitby) | Intended for measurement of size distribution rather than mass concentration. Development might enable use of this method for mass concentration. |
| Condensation nucleic counter | Similar to light-scattering methods. Limited to lower concentrations. |
| Diffusion batteries<br>Lidar<br>Holography | Limited potential. |

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a/ Compliance monitoring applications only. Comments not meant to assess suitability of methods for research applications.

was presently developed to the point that it could be used for determining compliance without serious limitations or disadvantages. Most of the methods were judged to have unacceptable limitations.

A number of other more advanced techniques and methods were also included in our review. These techniques include acoustic attenuation, pressure drop across a nozzle, pressure drop across a filter, unbalance of a centrifuge, acoustic particle counting, hot-wire anemometry, decrease in natural frequency of a vibrating band or wire, automatic weighing, tape-spot photometry, light scattering photometry or nephelometry, lidar, single particle light scattering, holography, electrostatic particle bounce, electrostatic probe-in-nozzle, electrostatic ion capture, and electrostatic contact charging. Although some of these techniques may be useful for other effluent measurements, each has at least one serious limitation for the monitoring of particulate mass emissions.

A more complete review of most of these methods was conducted by Thermo-Systems, Inc., under contract from the Environmental Protection Agency. Their report contains a more complete description of each method and the advantages and disadvantages of each.[74] A summary of this work was also published in Ref. 75.

The methods selected and recommended for determining compliance with each type of emission regulation for fine particles selected in Chapter 4 are presented in the following sections.

## Compliance Monitoring Methods for Plume Opacity

Stringent plume opacity regulations will present problems in regard to the monitoring of sources for compliance with these standards. The main technique currently used to determine compliance with opacity standards is to utilize trained observers. The "calibrated eyeball" method of judging densities and opacities of plumes is adequate for the large majority of situations confronting air pollution control agencies at the present time. However, visual evaluation of plume opacity will probably not be adequate to judge compliance with stringent plume opacity regulations (5% or 10% opacity).

Reproducibility of readings for opacity of plumes is already a problem in enforcing existing opacity regulations. Currently, an observer is required to reproduce his reading of opacity usually within 10% of actual plume transmittance. The ability of observers to accurately read Ringelmann No. 1 or 20% equivalent opacity has been questioned.[76] In response to this question, the Bay Area Air Pollution Control District (BAAPCD) has stated that BAAPCD inspectors can now read Ringelmann No. 1 or equivalent opacity with an error of ± 1 Ringelmann number.[77] With improved calibration it is believed that the error can be reduced to ± 1/2 Ringelmann number. Thus, a Ringelmann No. 1 (20% opacity) would be read between 1/2 (10% opacity) and 1-1/2 (30% opacity). Based on the above comments, an opacity regulation of 20% opacity seems to be the most stringent regulation that can be enforced by use of trained observers.

A trained observer also has difficulty in adequately evaluating a wet plume or a detached plume. For an emitted aerosol that does not change in the atmosphere except to become diluted with air, relative opacity at the emission point is a reasonable measure of the potential effect it will have on visibility downwind of the source. But in the case of the wet plume and the detached plume, the apparent opacity at the emission point has no relationship whatsoever with the visibility reduction downwind of the source.

Many industrial effluents are saturated with moisture at temperatures above ambient, and in many situations the plume from such operations will be highly opaque. The effluent from most wet scrubbers fits in this category, and the apparent opacity of the plume bears more relationship to ambient temperature and humidity than the amount of pollutant being emitted to the atmosphere. Since high-efficiency wet scrubbers are candidates for the control of fine particle emissions from many sources, a problem would exist for a trained observer attempting to judge the compliance of these control systems with stringent opacity regulations.

The stack effluent from the burning of high sulfur fuel oil or high sulfur waste gas can very often produce what is known as a "detached plume" when the atmosphere is cool and humid. In this situation the gases immediately above the emission point may be essentially transparent, but at some distance downwind of the emission point a plume develops, presumably from the formation of sulfuric acid droplets produced from mixing cool, moist air with the $SO_3$ in the exhaust gases.

In view of the limitations of the trained observer, instrumental evaluation of plume opacity will undoubtedly be required if stringent opacity regulations are imposed. The best instrumental method currently available to monitor the opacity of particulate emissions is the on-stack transmissometer. Commercial transmissometers with a variety of designs are available for measuring the in-stack opacity of particulate emissions. For these instruments to properly measure the in-stack opacity and for the measurement to reflect the opacity of the plume emitted by the source, standardization of performance and installation specifications will be necessary. EPA has prepared a set of proposed specifications for transmissometers and, in addition, has initiated a program to evaluate the performance of a commercially available transmissometer as a continuous monitor of the in-stack opacity, plume opacity and in-stack mass concentration of particulates for several different types of sources.

The Texas Air Control Board has investigated the use of a transmissometer in over 100 installations in various industrial plants in the State of Texas.78,79/ The types of processes investigated include: (1) alumina kilns; (b) carbon black furnaces; (c) cement kilns; (d) copper smelters; (e) fluid catalytic cracking units; (f) glass furnaces; (g) incinerators; (h) lignite-fired boilers; and (i) instant coffee driers. Because of the mostly favorable experience, the State of Texas has amended their regulations to make use of the transmissometer instrument mandatory. Effective in December 1973, all industrial processes producing visible emissions must install a transmissometer instrument on the stack if the total flow rate is in excess of 100,000 cfm. Consideration is being given to reducing this minimum flow rate to 50,000 cfm in order to cover more of the sources of visible emissions in the State of Texas.

Previous experience has pinpointed some disadvantages in the use of transmissometer instruments. One of the major problems in some applications occurs in rechecking the zero and span adjustments of the instrument. However, recent advances in instrumentation have resulted in the availability of an instrument with an automatic calibration sequence.79,80/ Some problems have also occurred because of dirt in the flue gases depositing on the optical surfaces of the instrument, giving unrealistically low readings. If the instrument is readily accessible, cleaning the optical surfaces every few hours to insure accurate readings is not an excessive burden although obviously some labor cost is involved. However, if the instrument is mounted several hundred feet up on a stack and is accessible only by an exposed ladder, frequent cleaning becomes an even greater burden. This problem can be reduced by proper design of the installation although it may never be completely eliminated. The common practice with a negative pressure stack is to leave a small space between the mating flanges where the light source is bolted to the pipe which extends through the stack so that outside air is aspirated into the slot, passes across the optical surface, and then through the pipe, into the stack, and out the top of the stack. A similar arrangement is provided on the other side where the bolometer or other detector is mounted. With a positive pressure stack, a sparging point is placed in the flanges and clean air is forced in under pressure to sweep across the optical surfaces. Some installations of this type have been quite successful and lens cleaning is only required at very infrequent intervals, sometimes as long as a month or more. In other cases, especially where the particulate matter in the stack is sticky or gummy, these measures have been only partially successful. The transmissometer being marketed by

Lear-Siegler, Inc., is equipped with high volume air purging attachments to keep the optical windows free of dirt deposits. The purge air is supplied by one or two blowers with filters, depending on pressure conditions within the stack or duct. If the pressure is very negative, filters alone can be used to clean the air drawn into the instrument.

As was the case with direct visual observation, effluent streams that contain condensed water vapor present operational difficulties for transmissometers. Experience has shown that these instruments cannot operate properly in stacks with an appreciable amount of condensed water vapor. Such problems can be avoided by withdrawing a portion of the flue gas, passing this stream through a heated chamber to raise the temperature above the dew point, and making a measurement in this chamber, after which the sample stream is then returned to the stack.[79,81] However, very few installations of this type have been constructed and operated successfully, and moisture condensation remains a problem in certain types of industrial operations.[79]

Even utilizing variations in transmissometer techniques, like those described above, it is still not possible to representatively measure plume opacity in those cases where condensation of hydrocarbons or other gaseous pollutants occurs beyond the stack (i.e., detached plume). Even though the definition of "fine particulate" may include these condensing vapors, the phenomenon occurs in so few effluent streams and usually only under such specific atmospheric conditions that this situation does not impair the otherwise wide applicability of the transmissometer method.

In summary, it is our opinion that the transmissometer has been developed and tested sufficiently to justify recommending it as a method that can be used for monitoring the opacity of effluent streams in order to determine compliance with 5% or 10% opacity standards.

### Compliance Monitoring Methods for Mass Emissions

Determination of compliance with an emission standard based on the utilization of best installed technology or the potential-emission rate concept will require the measurement of the concentration of mass of fine particulates emitted for a source. Because a measurement of the mass of fine particulate is involved in both cases, one monitoring procedure can probably be developed for use with either standard. The specific requirements for compliance monitoring associated with each type of standard are briefly summarized in the following paragraphs.

Emission standards for fine particles based on best installed technology will require a monitoring method which measures the concentration (grains/ft$^3$) of fine particulate in the inlet and outlet of the control device.

If the quantity of gas into and out of the control device is significantly different because of use of dilution air or vaporization of water, etc., then it would be necessary to determine efficiency on the basis of pounds per hour of fine particles at the inlet and the outlet. This means that in addition to determining the concentration of fine particles, the gas flow rate may also have to be determined by a velocity traverse in the inlet and outlet ducting. Standards which utilize the concept of potential-emission rate will require a monitoring method which measures the concentration of fine particulates (grains/$ft^3$) and the total gas flow (cfm). Continuous monitoring on both variables would be difficult.

Based on our review of potential methods that might be used in this application, we have selected a manual method involving the use of a sampling probe with a 2 µm cut-off cyclone preceding a filter, similar to the EPA sampling train, or an in-stack system as depicted in Figure 13. This method of determining the concentration of fine particles has the disadvantage of being a manual method.

This recommended manual method, consisting of a cutoff cyclone followed by a filter, would need to be modified if "particulates" are defined to include material that exists as a particle at conditions of standard temperature and pressure. The effluent stream may contain condensible vapors which would not be collected by the filter in the recommended sampling method if the sampling is conducted at temperatures above standard. Indeed, it is desirable to maintain the sampling temperature above the dew point of the effluent gas stream. Therefore, when the effluent stream may contain significant quantities of condensibles, it will be necessary to follow the filter with impingers immersed in an ice bath.

A continuous monitoring method would be preferable to a manual method, but none are available at present that, in our assessment, would be satisfactory for monitoring the concentration of fine particles. The best potential method that might be further developed for this purpose is the beta-tape device. Although the beta-tape is a semicontinuous monitoring method, it does appear to have possibilities for monitoring the fine particles in a sample stream from a cutoff cyclone as depicted in Figure 14.[74/]

Several particle collection techniques other than filters can be used with beta-radiation attenuation. Among these are impactors and electrostatic precipitators and possibly thermal precipitators. Further investigation is necessary to fully evaluate each collection method for use with the beta monitor. Reference 82 reports the results of field and laboratory tests conducted to evaluate inertial sizing techniques, cascade impactors and cyclones, for field measurements of control device efficiency as a function

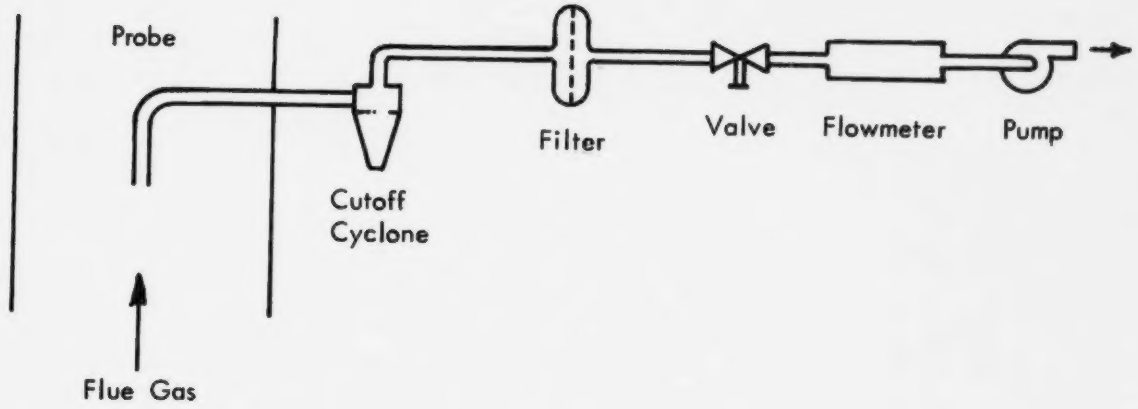
Probe
Cutoff
Cyclone
Filter
Valve
Flowmeter
Pump
Flue Gas

Figure 13. Recommended manual method for monitoring compliance of sources with fine particle emission regulations

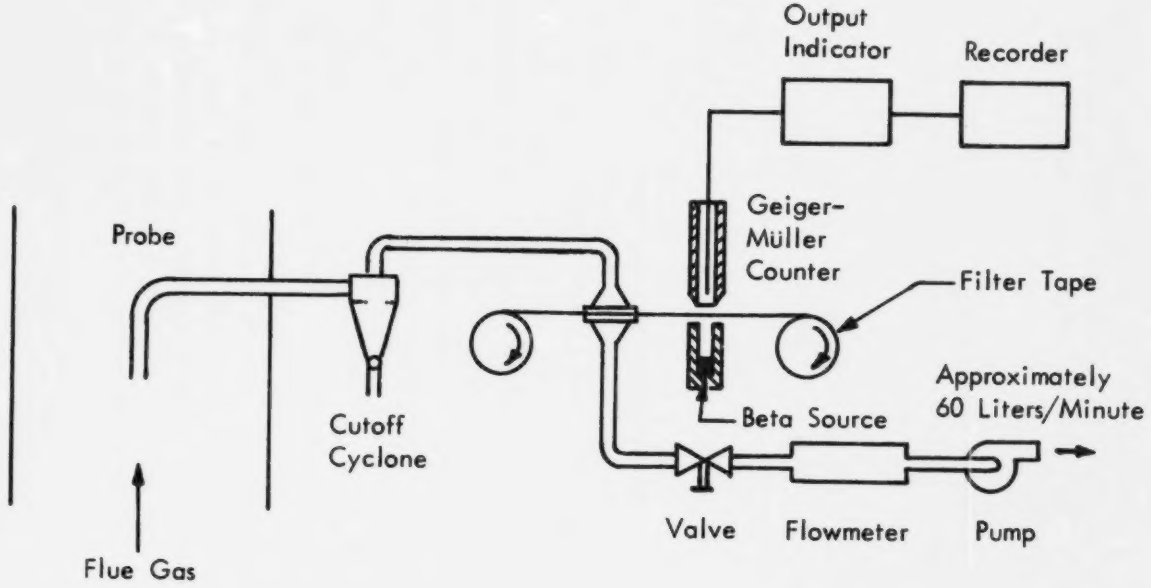
Output
Indicator
Recorder
Probe
Geiger-
Müller
Counter
Filter Tape
Approximately
60 Liters/Minute
Beta Source
Cutoff
Cyclone
Valve
Flowmeter
Pump
Flue Gas

Figure 14. Semicontinuous method for monitoring fine particle emissions

of particle size. One of the conclusions of the study was that no single inertial sizing device was suitable for all the sampling circumstances encountered on a wide variety of stationary emission sources. The results of the work reported in Ref. 82 suggest that it will be necessary to modify monitoring techniques to suit specific source types.

As noted in Chapter 4, the State of New Mexico has adopted a fine particle regulation for coal-burning equipment. This regulation limits emission of $< 2$ μm particles to 0.02 lb/$10^6$ Btu. The following test methods are recommended by the State of New Mexico.

Method 1 (Manual) - The sample is first passed through a cascade impactor (Andersen type) to remove $< 2$ μm particles. Particulate which escapes the impactor is collected on the integral filter.

Method 2 (Continuous) - The sample is passed through the impactor as above, and particulate which escapes the impactor is directed to an adhesive-coated quartz crystal microbalance.

Method 3 - Any method as accurate as Method 1 or 2.

The above Method 1 is similar to our recommended method except that the use of a cutoff cyclone is, we feel, subject to fewer inaccuracies and is much more amenable to continuous sampling. Method 2 of the New Mexico Regulation involves use of the quartz crystal microbalance (Figure 15). One possible problem with the piezoelectric microbalance is that particles must adhere to the surface strongly enough to overcome inertial forces of the vibrating crystal. Most testing of this device has been done on ambient particles and it appears that most particles smaller than 20 μm adhere well enough to be weighted.[74/] This device is relatively new and untried in effluent gas streams but it does have the desirable feature of high sensitivity for direct sensing of particulate mass. The primary problem with its use may be frequent need to replace or clean the crystal, and this must be evaluated along with testing the applicability on stack effluents before it could be recommended for compliance testing or monitoring. Even if this device is not applicable for continuous monitoring, further development may enable its use as a substitute for the cutoff cyclone-filter method, thereby eliminating the tedious task of conditioning and weighing of the filters.

Whether one uses the cutoff cyclone or a cascade impactor for the fractionation of the large and small particles, it is a requirement of both that a constant sample flow rate be used. Because the flow rate into the cutoff cyclone (or impactor) is fixed, it is difficult to sample the stack

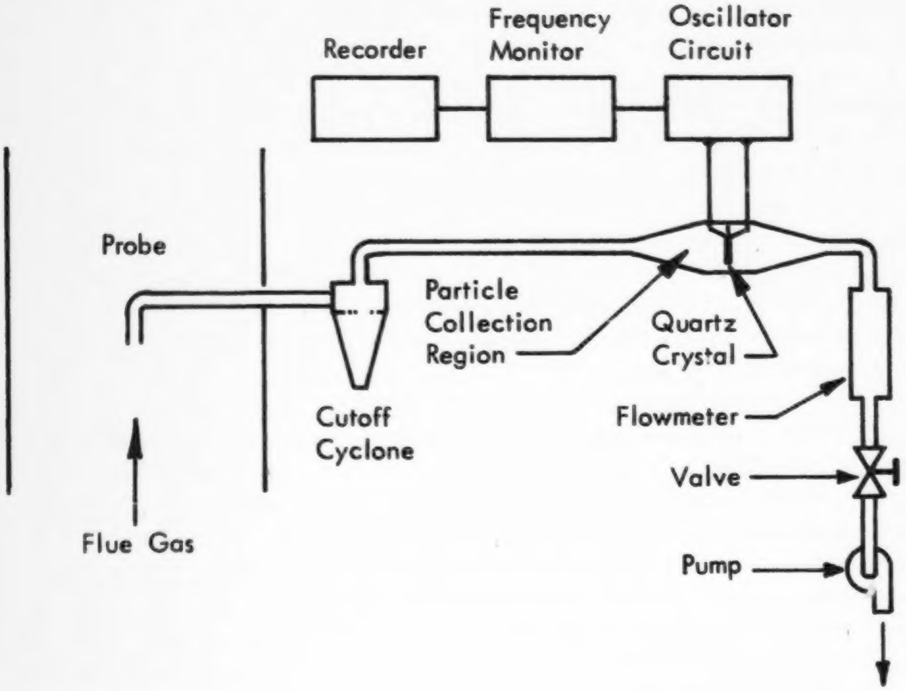
Recorder
Frequency Monitor
Oscillator Circuit
Probe
Particle Collection Region
Quartz Crystal
Cutoff Cyclone
Flowmeter
Valve
Pump
Flue Gas

Figure 15. Schematic diagram of monitoring system utilizing quartz crystal microbalance

gas isokinetically. However, this may not be necessary because the analyses are only concerned with the concentration of fine particles in the stack gas.

Studies of errors in sampling at anisokinetic conditions indicate that it is rarely necessary to bother about isokinetic sampling for particles of unit density below about 5 μm diameter.83-86/ Therefore, single point sampling would be representative. This conclusion assumes that problems of air-in-leakage, etc., in stacks which can cause localized concentration gradients in both the gases and particulates are negligible. Unless further experimental study develops evidence to the contrary, sampling can be conducted anisokinetically at a single point without significant error in order to measure fine particle concentrations by the methods previously discussed.

The recommended method will determine the concentration of fine particles and thereby yield the control device fine particle efficiency only if the effluent flow rate (SCFM) is the same at the inlet and outlet. If the flow rates (SCFM) are significantly different, a velocity traverse may also be necessary. A velocity traverse is also a manual method that would be very difficult to adapt to continuous measurement unless single-point measurements at the inlet and outlet were determined to be representative, and a calibration curve prepared to enable calculation of total flow based on velocity at the single point.

If currently available data on particle-size dsitribution of effluents were used to formulate the fine particle emission standard, some problems of equality in enforcement might result during the initial stages of the implementation of a mass emission standard using the recommended testing method. Most of the particle size distribution data currently available, which would be used to define the potential fine particle emission rate of sources, has been obtained by a variety of methods, e.g., ASME train-Bacho sizing, EPA train-Bacho sizing, and cascade impactors. Measurements of the mass fraction of fine particles by these methods probably differ considerably from those which would be obtained by the cutoff cyclone-filter method. Depending upon the extent of discrepancy, it may be necessary to measure fine particles emitted from a source by one of the more common previously used methods as well as by the cutoff cyclone-filter method. When an extensive data base has been developed using the recommended measuring method, it may be appropriate to modify the emission standard.

## SUMMARY OF RECOMMENDED COMPLIANCE MONITORING METHODS

Presently available methods for determining source compliance are amenable to use with the three types of emission standards considered for the regulation of fine particulate emissions. In the case of the opacity standard, the on-stack transmissometer can be used for continuous monitoring. For the standard based on best installed technology and the potential emission-rate, the manual methods of determining fine particle concentration by cutoff cyclone-filter and total gas flow by velocity traverse can be used. It also appears that both of these standards might make use of beta-tape instruments for continuous monitoring of the concentration of fine particles, which may be the only measurement necessary for compliance testing. Further development of the cutoff cyclone-piezoelectric crystal method may permit its use as a substitute for the cutoff cyclone-filter method to eliminate filter weighing and provide more immediate results.

# ECONOMIC IMPACT OF FINE PARTICLE EMISSION STANDARDS

## INTRODUCTION

Solutions to environmental problems require more than just improved or new technology. Economic problems must also be overcome. The supply of capital--whether private, corporate or government--is always limited. It is, therefore, imperative that the funds that are available are allocated in a way that will return the greatest benefits per dollar invested.

Adoption of emission standards based on particle size will increase the capital investment requirements of various industries and raise manufacturing costs by whatever amount is required to operate and maintain the air pollution control facilities. In this chapter, estimates of control costs are presented for selected industrial sources of fine particulates, and a limited analysis of the economic impact of the control costs on the selected industrial operations is also presented.

The capital and annual costs for control equipment required to meet emission standards based on particle size were determined using model plants for the selected industrial operations. Accurate description of the model plant for a specific operation requires knowledge of production rates, emission rates, carrier gas flow rates, effluent particle size distribution, stack diameter, etc. Data on the performance capability of control equipment and the capital and operating costs of control equipment as a function of collection efficiency and capacity (cfm) are also required.

The following sections of this chapter discuss (1) determination of cost versus efficiency relationships for control devices, (2) methodology for determining costs required for compliance with fine particle emission standards, (3) potential reduction in fine particle emissions resulting from implementation of fine particle emission standards, and (4) economic impact resulting from costs of control equipment required for compliance with emission standards for fine particles.

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## DETERMINATION OF COST VS EFFICIENCY RELATIONSHIPS FOR CONTROL DEVICES

During this program, a review of the literature and other available sources of data on control equipment costs was conducted. Numerous installations of control devices are described in the literature and prior EPA studies, but it is difficult to obtain sufficient information to correlate the costs of individual installations on a common basis.

Our analysis of available information indicated that the most comprehensive analysis of the cost of control equipment as a function of capacity has been presented in the EPA publication "Control Techniques for Particulate Air Pollutants."87/ Figure 16 illustrates typical data from Ref. 87. The format used in Figure 16 is not a convenient method of presentation of data. Other methods of data presentation were reviewed, and a format suggested by Ref. 88 was selected as being the most convenient for the purposes of the current study. Reference 88 indicates that for a given equipment capacity (cfm), equipment costs, either capital or annualized, plotted as a function of an efficiency factor (E/100-E) yield useful working relationships for estimating costs. The data from Ref. 87 are plotted in Figures 17 and 18 in the format suggested by Ref. 88 with equipment capacities (cfm) as a parameter. The data in Ref. 87 (as shown in Figure 16) present generalized efficiency ranges and only three values of the nominal efficiency of each control device can be assigned to the cost data given in Ref. 87. It was assumed that a linear relationship could be used to depict the data as shown in Figures 17 and 18.

The lines shown in Figures 17 and 18 represent our judgment of the best fit of available data for each equipment capacity (cfm). In the case of fabric filters, only one efficiency value is given in Ref. 87 and the relationship of cost to efficiency is not known. It seems probable that the cost of fabric filters would increase as the required efficiency is increased, because the higher efficiencies would generally require more cloth area per cfm (i.e., a lower air-to-cloth ratio). Therefore, we again assumed that the straight-line relationship is valid for fabric filters, and the lines were drawn with an arbitrary slope between that for electrostatic precipitators (ESP) and wet scrubbers.

It is evident from the above discussion that the cost vs efficiency relationships (Figures 17 and 18) are based on limited data and that it has been necessary to make several assumptions which could lead to errors in subsequent calculations. However, Figures 17 and 18 represent the best estimations that are possible based on available information.

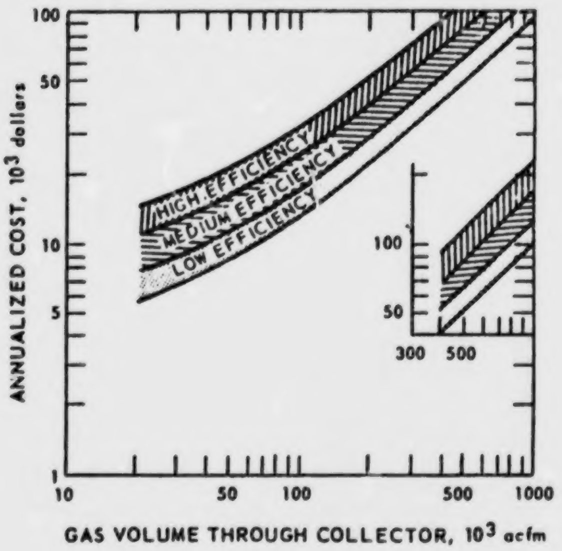

Figure 16. Annualized cost for operation of high-voltage[87/]
electrostatic precipitators

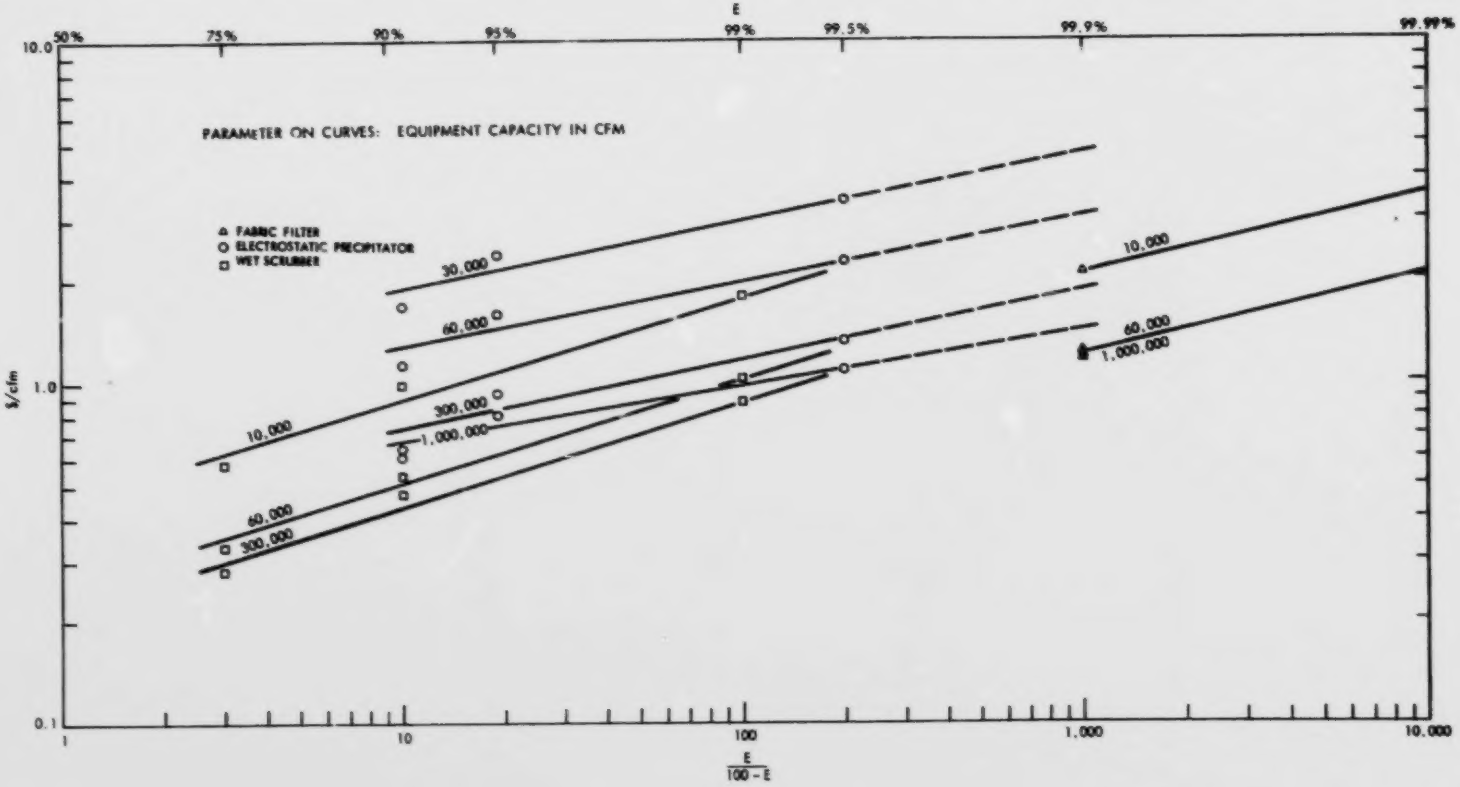

Figure 17. Installed costs for control equipment

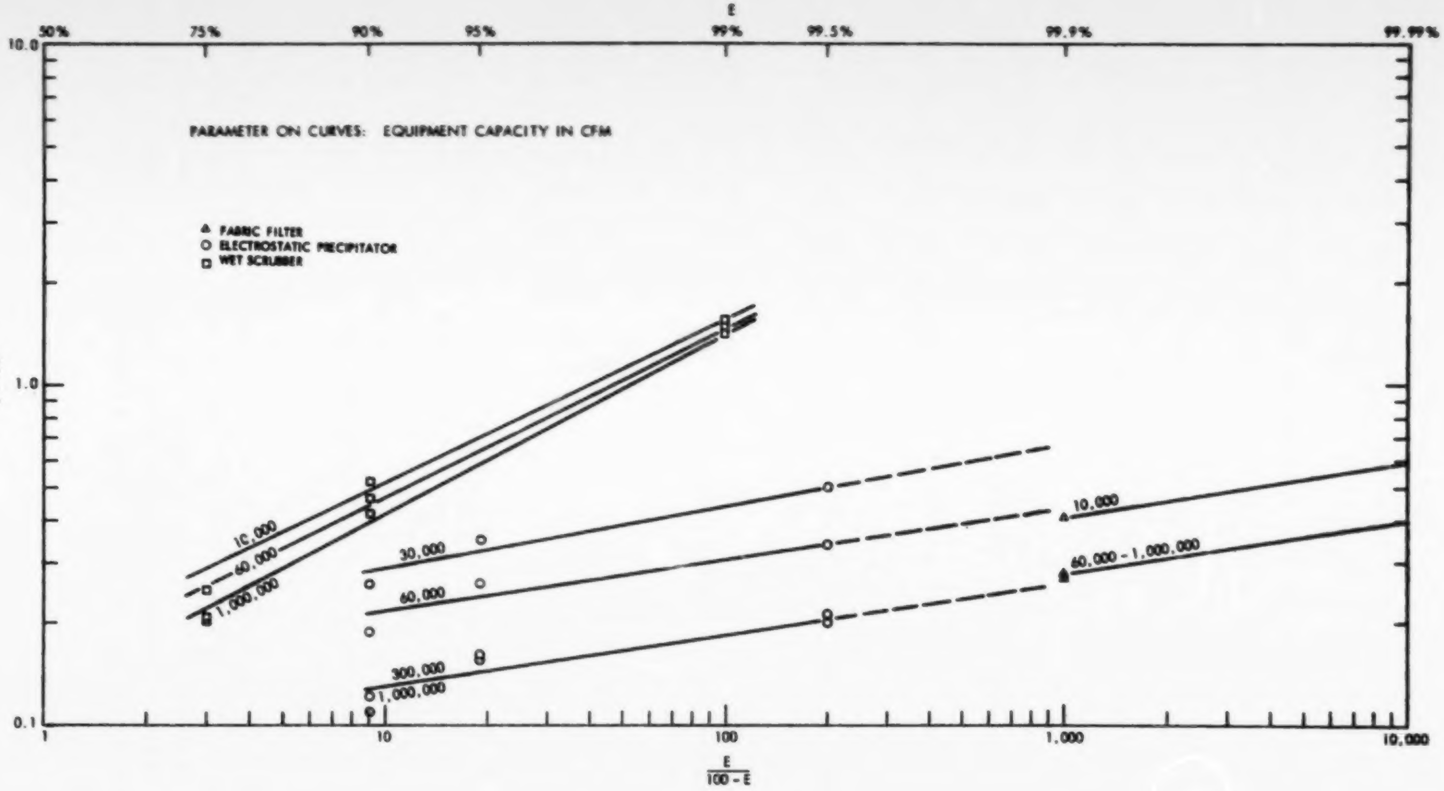

Figure 18. Annualized costs for control equipment

## METHODOLOGY FOR DETERMINING COSTS REQUIRED FOR COMPLIANCE WITH FINE PARTICLE EMISSION STANDARDS

The determination of the control costs required for compliance with various emission standards for fine particles involves the following major steps:

1. Development of model plants for each industry category.

2. Determination of control-device performance required to meet a specific emission standard for fine particles.

3. Determination of costs for model plant and industry for compliance with specific emission standard for fine particles.

General details involved in each of these steps are discussed in the following subsections.

### Development of Model Plants for Important Industrial Sources of Fine Particle Emissions

A review of the literature and previous EPA industry studies was conducted in order to formulate "model plants" for each important source of fine particle emissions. The objective of this activity was to select an average or representative size plant in terms of production rate. Other important parameters for these model plants were carrier gas flow rate and temperature, emission rate of particulates, particle size distribution of emitted particulates, and "best installed control device" (type and efficiency).

In several industries the model plant consisted of only one source such as a coal-fired power plant or a cement kiln. Other categories were divided into two or three model plants because of the different types of sources (ferroalloy furnaces). In still other cases only one model plant was selected but it consisted of several different sources and more than one control device (primary nonferrous).

It was not possible to develop model plants and carry out the cost calculations for all sources because of lack of information--especially particle size distribution data. However, an attempt was made to carry out these calculations for the most important industrial sources of fine particles even though it was necessary in some cases to make generalizations and assumptions.

Model plant sizes were selected with the realization that such a generalization does not truly reflect the situation for those plants that are much smaller or much larger. However, the primary concern of this study was the total industry impact so it was felt that use of the model plant was justified.

## Determination of Control Device Performance Requirements

Control equipment costs presented in Figures 17 and 18 are based on the overall mass efficiency of the control equipment. In order to utilize these data to determine costs, the control device performance requirements necessary to achieve a fine particle emission standard must be translated into overall mass efficiency. The specific standards that will be considered in the calculation of costs are: (1) plume opacities of 10% and 5%, and (2) utilization of the best installed technology. Although the potential emission rate concept offers one of the most direct methods for regulating fine particle emissions, calculations of control equipment costs were not performed for this type of regulation because of the need for more detailed and extensive source testing to determine both potential emission rates and source compliance requirements.

The techniques used to translate the plume opacity and best installed technology standards into overall mass efficiency requirements are presented in the following subsections.

Control Device Performance Requirements for Plume Opacity Standards - An opacity regulation is perhaps the most difficult to translate into terms of overall mass efficiency required of control equipment. A suitable relationship between plume opacity and particulate properties and stack diameter must be used to determine the degree of collection efficiency required to meet a plume opacity standard. Ensor and Pilat have recently developed a procedure for calculating plume opacity from particulate air pollutant properties.[68] (Also see Chapter 5.) These authors developed the following equation to calculate the expected mass concentration for various values of plume transmittance (or opacity), average particle density, and plume diameter.

$$W = -K \rho/L \ln (I/Io) \qquad (4)$$

In Eq. (4),

W = Total particulate mass concentration of plume (i.e., grain loading),

ρ = Average particle density,

L = Diameter of plume,

I/Io = Light transmittance,

$$K = \frac{\text{Specific particulate volume}}{\text{Extinction coefficient ratio.}}$$

The parameter K is a function of the particle size distribution, the refractive index of the particulate, and the wavelength of incident light. Reference 68 presents graphs of K versus the geometric mass mean particle radius with the geometric standard deviation of the particle size distribution and the refractive index of the particles as parameters.

The grain loading from an uncontrolled source was determined by using the effluent flow rate from the model plant, the production rate of the model plant, and the appropriate emission factor. Equation (4) was then used to compute the grain loading of a controlled source corresponding to the opacity limitation for each model plant. In some cases the characteristics of the particles (parameters $\rho$ and K) were not available, and it was necessary to assume that they were approximately equivalent to other similar sources for which the data were available.

When data were available to permit calculation of the outlet grain loading corresponding to a selected opacity, the efficiency of the control device required was calculated from Eq. (5) assuming no dilution of the stack gases.

$$\text{Efficiency} = \frac{\text{Inlet Grain Loading - Outlet Grain Loading}}{\text{Inlet Grain Loading}} \tag{5}$$

In order to determine, from Figures 17 and 18, the cost of the control device with the efficiency determined from Eq. (5), it is necessary to specify the type of control device. If more than one type of control device could provide the required efficiency and function on the given source, the selection of the type of control device was based on knowledge of usual industry practice and lowest cost.

Control Device Performance Requirements for Best Installed Technology Standard - The emission standard based on the installation of best installed control technology on all plants would require that all sources in each industrial category be equipped with control equipment that is at least as efficient as that of the best control device that has been installed on each type of plant in recent years. Our data base was used to identify this "best installed control device" (BICD) for each industry category and its overall efficiency. This device was not necessarily the highest efficiency device available, but rather the best that is generally being installed in a given industry at the present time.

### Costs to Model Plant and Industry for Compliance with Specific Fine Particle Emission Standards

The procedure for determining the costs for compliance with specific fine particle emission standards is illustrated in detail in Appendix B using coal-fired power plants as an example. Only the results of the calculations will be presented for the various sources in the following subsections. The annualized costs associated with the control devices were based on 8,000 hr of operation per year. Not all plants operate that many hours, and indications of the likely operating hours are given for those industries which differ significantly from the assumed 8,000 hr/year.

Coal-Fired Power Plants - Table 16 presents the estimated control equipment costs for coal-fired electric utility plants. An electrostatic precipitator with an overall mass efficiency of 99% was selected as the best installed control device (BICD). The overall collection efficiencies, computed from Eq. (4) using effluent property data from Refs. 68,60,61 required to achieve the 10 and 5% opacity regulations are 99.66 and 99.83%. Electrostatic precipitators were chosen as the control devices that would be used to achieve compliance with the opacity standards.

A comparison of the incremental annualized costs for compliance with the fine particle regulations is presented in Table 17. Since only a small percentage of electric utility plants are currently equipped with the BICD, it was assumed that all existing plants would have to install new control devices to meet all the regulations. The incremental annualized costs shown in Table 17 for the case where all the electric utility plants are required to install the BICD are based on the preceding assumption.. The incremental costs for the opacity regulations represent the difference between the costs associated with the opacity regulations and the BICD regulation.

Estimates of the reduction in fine particle emissions from coal-fired power plants that would result from installation of control equipment required for compliance with the emission standards for fine particles are also presented in Table 16. Currently, fine particle emissions from the total industry are estimated at 243,000 lb/hr. Installation of the best installed control system on all plants would reduce emissions to 15,000 lb/hr--a 94% reduction. Compliance with a 10% opacity regulation would reduce the emissions to 5,050 lb/hr (a 97% reduction), while compliance

Table 16. CONTROL EQUIPMENT COSTS FOR COAL-FIRED ELECTRIC UTILITY PLANTS

| | | Model Plant | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 400 mw (100% load) | 150,000 mw |
| | Coal burned | $1.2 \times 10^6$ tons/year at 68.5% load factor | $258 \times 10^6$ tons/year |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 3,700 lb/hr | 796,000 lb/hr |
| | (b) Present | _____[a] | 243,000 lb/hr |
| II. | Best installed control system[b] | | |
| | Installed cost | $\$1.03 \times 10^6$ | $\$386 \times 10^6$ |
| | Annualized cost | $\$0.19 \times 10^6$/year | $\$71 \times 10^6$/year |
| | Fine particle emissions | 69.1 lb/hr | 15,000 lb/hr |
| III. | 10% Opacity regulation[c] | | |
| | Installed cost | $\$1.4 \times 10^6$ | $\$525 \times 10^6$ |
| | Annualized cost | $\$0.25 \times 10^6$/year | $\$94 \times 10^6$/year |
| | Fine particle emissions | 23.5 lb/hr | 5,050 lb/hr |
| IV. | 5% Opacity regulation[d] | | |
| | Installed cost | $\$1.57 \times 10^6$ | $\$589 \times 10^6$ |
| | Annualized cost | $\$0.30 \times 10^6$/year | $\$112 \times 10^6$/year |
| | Fine particle emissions | 11.7 lb/hr | 2,510 lb/hr |

---

[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is 99% efficient electrostatic precipitator.

[c] Control device required to meet standard is 99.66% efficient electrostatic precipitator.

[d] Control device required to meet standard is 99.83% efficient electrostatic precipitator.

Table 17. INCREMENTAL ANNUALIZED COSTS FOR COAL-FIRED ELECTRIC UTILITY PLANTS TO MEET FINE PARTICLE EMISSION STANDARDS

| Emission Standard | Control System | Annualized Cost ($/Year) | | Incremental Annualized Cost ($/Year) | |
|---|---|---|---|---|---|
| | | Model Plant | All Plants | Model Plant | All Plants |
| All plants install best installed control device (BICD) | 99% Efficient electrostatic precipitator (BICD) | 190,000 | $71 \times 10^6$ | 190,000 | $71 \times 10^6$ |
| 10% Opacity | 99.66% Efficient electrostatic precipitator | 250,000 | $94 \times 10^6$ | 60,000 | $23 \times 10^6$ |
| 5% Opacity | 99.83% Efficient electrostatic precipitator | 300,000 | $112 \times 10^6$ | 50,000 | $18 \times 10^6$ |

with a 5% opacity regulation would further reduce the emissions to 2,510 lb/hr (a 99% reduction). In making the above estimates of emission reductions, the control device was assumed to be available and operating at peak efficiency at all times.

Iron and Steel Plants - The costs for compliance with fine particle emission regulations were estimated for three of the major sources of particulate pollutants in iron and steel plants--sinter machines, basic oxygen furnaces, and electric arc furnaces. Open hearth furnaces were not included because these furnaces are gradually being phased out of production. The cost estimates for the three sources are presented separately in the following sections.

Sinter machine - Estimated control equipment costs for sinter machines are presented in Table 18. A model plant with a production capacity of 4,000 tons/day (1.46 x $10^6$ tons/year) was used as a basis for the calculations. Sinter plants in current use in the industry range in capacity from 800 to 14,000 tons/day. For this source, 10% and 5% opacity regulations would not require the installation of control equipment that is as efficient as the best installed control device (i.e., a fabric filter system). Since only about 19% of the existing sinter machines are equipped with fabric filters and electrostatic precipitators are the prevalent control systems in use, electrostatic precipitators were selected for compliance with the opacity standards.

Table 19 gives a comparison of the incremental annualized costs for compliance with the fine particle regulations. The costs given in Table 19 reflect the fact that 19% of the existing sinter machines are already equipped with fabric filters.

The potential reduction in fine particle emissions resulting from implementation of an emission standard for fine particles for all sinter machines ranges from 48.5 to 96%.

Basic oxygen furance - Control equipment costs for basic oxygen furnaces in iron and steel plants are shown in Tables 20 and 21. The model furnace selected as the basis for the estimates of control costs was assumed to have a capacity of 1 x $10^6$ tons/year or 200 tons/heat. The costs presented in Tables 20 and 21 recognize the fact that 20% of the existing basic oxygen furnaces are already equipped with the best installed control device.

Implementation of an emission regulation for fine particles could result in a significant reduction in fine particulate emissions from basic oxygen furnaces.

## Table 18. CONTROL EQUIPMENT COSTS FOR SINTER MACHINE (WINDBOX) (IRON AND STEEL PLANTS)

| | | Model Plant | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 4,000 tons/day | $90 \times 10^6$ tons/year |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 116 lb/hr | 7,150 lb/hr |
| | (b) Present | ___[a] | 1,400 lb/hr |
| II. | Best installed control system[b] | | |
| | Installed cost | $\$1 \times 10^6$ | $\$49.9 \times 10^6$[c] |
| | Annualized cost | $227,000/year | $\$11.3 \times 10^6$/year[c] |
| | Fine particle emissions | 1.04 lb/hr | 64 lb/hr |
| III. | 10% Opacity regulation[d] | | |
| | Installed cost | $770,000 | $\$38.4 \times 10^6$[c] |
| | Annualized cost | $146,000/year | $7.3 \times 10^6$/year[c] |
| | Fine particle emissions | 14.2 lb/hr | 722 lb/hr[c] |
| IV. | 5% Opacity regulation[e] | | |
| | Installed cost | $850,000 | $\$42.4 \times 10^6$[c] |
| | Annualized cost | $162,000/year | $\$8.1 \times 10^6$/year[c] |
| | Fine particle emissions | 6.9 lb/hr | 354 lb/hr[c] |

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[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is a fabric filter.

[c] Based on fact that approximately 19% of sinter machines are already equipped with fabric filter.

[d] Control device selected to meet standard is 98.6% efficient electrostatic precipitator.

[e] Control device selected to meet standard is 99.4% efficient electrostatic precipitator.

Table 19. INCREMENTAL ANNUALIZED COSTS FOR SINTER MACHINES (IRON AND STEEL) TO MEET FINE PARTICLE EMISSION STANDARDS

|  |  | Annualized Cost ($/Year) |  | Incremental Annualized Cost ($/Year) |  |
|---|---|---|---|---|---|
| Emission Standard | Control System | Model Plant | All Plants | Model Plant | All Plants |
| 10% Opacity | 98.6% Efficient electrostatic precipitator | 146,000 | $7.3 \times 10^6$ | 146,000 | $7.3 \times 10^6$ |
| 5% Opacity | 99.4% Efficient electrostatic precipitator | 162,000 | $8.1 \times 10^6$ | 16,000 | $0.8 \times 10^6$ |
| All plants install BICD | Fabric filter | 227,000 | $11.3 \times 10^6$ | 65,000 | $3.2 \times 10^6$ |

## Table 20. CONTROL EQUIPMENT COSTS FOR BASIC OXYGEN FURNACES (IRON AND STEEL PLANTS)

| | | Model Plant | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 1 x $10^6$ cons/year<br>(200 tons/heat) | 80 x $10^6$ tons/year |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 10,700 lb/hr | 400,000 lb/hr |
| | (b) Present | ______[a] | 43,600 lb/hr |
| II. | Best installed control system[b] | | |
| | Installed cost | $960,000 | $61.5 x $10^6$[c] |
| | Annualized cost | $163,000/year | $10.4 x $10^6$/year[c] |
| | Fine particle emissions | 32 lb/hr | 2,560 lb/hr |
| III. | 10% Opacity regulation[b,d] | | |
| | Installed cost | $1 x $10^6$ | $80 x $10^6$ |
| | Annualized cost | $177,000/year | $14.2 x $10^6$/year |
| | Fine particle emissions | 19 lb/hr | 1,540 lb/hr |
| IV. | 5% Opacity regulation[e] | | |
| | Installed cost | $960,000[f] | $77 x $10^6$ |
| | Annualized cost | $207,000/year | $16.5 x $10^6$/year |
| | Fine particle emissions | 10 lb/hr | 800 lb/hr |

---

[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is 99.7% efficiency electrostatic precipitator. This is a very high efficiency for an electrostatic precipitator operating on a source emitting essentially 100% < 3 µm particulates, and, in fact, this efficiency is inconsistent with fractional efficiency data for electrostatic precipitators. However, the particle size distribution at the exit of the furnace may not be what the electrostatic precipitator "sees" (i.e., agglomeration may occur before the particulate reaches the control device).

[c] Based on fact that approximately 20% of basic oxygen furnaces are already equipped with 99.7% efficiency electrostatic precipitator.

[d] Control device required to meet standard is 99.8% efficiency electrostatic precipitator.

[e] Control device required to meet standard is 99.91% efficiency fabric filter.

[f] Installed cost of 99.91% efficiency fabric filter is the same as for 99.7% electrostatic precipitator, but annualized cost is higher.

Table 21. INCREMENTAL ANNUALIZED COSTS FOR BASIC OXYGEN FURNACES TO MEET FINE PARTICLE EMISSION STANDARDS

| Emission Standard | Control Systems | Annualized Cost ($/Year) | | Incremental Annualized Cost ($/Year) | |
|---|---|---|---|---|---|
| | | Model Plant | All Plants | Model Plant | All Plants |
| All plants install BICD | 99.7% Efficient electrostatic precipitator | 163,000 | $10.4 \times 10^6$ | 163,000 | $10.4 \times 10^6$ |
| 10% Opacity | 99.8% Efficient electrostatic precipitator | 177,000 | $14.2 \times 10^6$ | 143,000 | $4.2 \times 10^6$ |
| 5% Opacity | 99.91% Efficient fabric filter | 207,000 | $16.5 \times 10^6$ | 30,000 | $2.3 \times 10^6$ |

Installation of the BICD on all sources could reduce emissions from 43,600 lb/hr to 2,560 lb/hr--a reduction of 94.5%. The more stringent opacity regulations could result in a reduction of 96.5 to 98%.

Electric arc furnaces - A model furnace with a capacity of 80 tons/heat was used as the basis for the estimates of control equipment costs presented in Tables 22 and 23. Electric arc furnaces represent a relatively well controlled source with 65% of existing furnaces already equipped with fabric filters. Costs presented in Tables 22 and 23 reflect this fact.

The costs given in Table 22 show that the annualized cost associated with the opacity standards are lower than that for the best installed control device and reflect the fact that these standards require a control efficiency that is lower than that of the best installed control system (i.e., the fabric filter). However, the installed cost of the control device selected for the 5% opacity standard is higher than that for the best installed control system. It would, therefore, be reasonable to assume that the higher efficiency best installed control system might be chosen to meet the 5% opacity standard, but this depends on whether the choice is made on the basis of installed cost or annualized cost.

The estimated reduction in fine particle emissions that might be achieved by implementation of fine particle emission standards ranges from 71% for 10% opacity to 82% for the best installed control system.

Cement Plants (Rotary Kilns) - In this source category, control equipment costs for compliance with fine particle emission standards were estimated only for the rotary kiln--the major emission source in a cement plant. A cement plant with a production capacity of 3 x $10^6$ barrels/year was chosen as the basis for the model plant used to estimate the control equipment costs. Cement plants range in size from 1-14 x $10^6$ barrels/year production with approximately 50% of the plants in the capacity range of 2-4 x $10^6$ barrels/year.

Tables 24 and 25 summarize the estimated costs for compliance with the fine particle emission standards. For cement kilns, the opacity regulations are less stringent than the standard requiring the use of the best installed control device on all sources. The cost estimates shown in Tables 24 and 25 reflect the fact that approximately 17% of the cement kilns are already equipped with the best installed control device--a fabric filter system.

## Table 22. CONTROL EQUIPMENT COSTS FOR ELECTRIC ARC FURNACES (IRON AND STEEL PLANTS)

| | | Model Plant | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 80 tons/heat | 10 to 250 tons/heat |
| | Production | 100,000 tons/year | $21.5 \times 10^6$ tons/year |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 127 lb/hr | ≤7,400 lb/hr |
| | (b) Present | ____[a] | 3,600 lb/hr |
| II. | Best installed control system[b] | | |
| | Installed cost | \$182,000 | $\$13.7 \times 10^6$[c] |
| | Annualized cost | \$41,000/year | $\$3.1 \times 10^6$/year[c] |
| | Fine particle emissions | 3 lb/hr | 645 lb/hr |
| III. | 10% Opacity[d] | | |
| | Installed cost | \$161,000 | $\$12.1 \times 10^6$[c] |
| | Annualized cost | \$28,000/year | $\$2.1 \times 10^6$/year[c] |
| | Fine particle emissions | 8.2 lb/hr | 1,036 lb/hr[c] |
| IV. | 5% Opacity[e] | | |
| | Installed cost | \$204,000 | $\$15.4 \times 10^6$[c] |
| | Annualized cost | \$32,000/year | $\$2.4 \times 10^6$/year[c] |
| | Fine particle emissions | 3.5 lb/hr | 683 lb/hr[c] |

---

[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is a fabric filter.

[c] Based on fact that approximately 65% of electric arc furnaces are already equipped with fabric filters.

[d] Control device selected to meet standard is 95.8% efficient electrostatic precipitator.

[e] Control device selected to meet standard is 98.2% efficient electrostatic precipitator.

Table 23. INCREMENTAL ANNUALIZED COSTS FOR ELECTRIC ARC FURNACES TO MEET FINE PARTICLE EMISSION STANDARDS

| | | Annualized Cost ($/Year) | | Incremental Annualized Cost ($/Year) | |
|---|---|---|---|---|---|
| Emission Standard | Control System | Model Furnace | All Furnaces | Model Furnace | All Furnaces |
| 10% Opacity | 95.8% Efficient electrostatic precipitator | 28,000 | $2.1 \times 10^6$ | 28,000 | $2.1 \times 10^6$ |
| 5% Opacity | 98.2% Efficient electrostatic precipitator | 32,000 | $2.4 \times 10^6$ | 4,000 | $0.3 \times 10^6$ |
| All furnaces install BICD | Fabric filter | 41,000 | $3.1 \times 10^6$ | 9,000 | $0.7 \times 10^6$ |

## Table 24. CONTROL EQUIPMENT COSTS FOR CEMENT PLANT ROTARY KILNS

| | | Model Plant | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 3 x $10^6$ barrels/year | 550 x $10^6$ barrels/year |
| | Production | | 400 x $10^6$ barrels/year |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 1,325 lb/hr | 243,000 lb/hr |
| | (b) Present | ____[a] | 44,300 lb/hr |
| II. | Best installed control system[b] | | |
| | Installed cost | $462,000 | $70.3 x $10^6$[c] |
| | Annualized cost | $102,000/year | $15.5 x $10^6$/year[c] |
| | Fine particle emissions | 11 lb/hr | 2,000 lb/hr |
| III. | 10% Opacity[d] | | |
| | Installed cost | $440,000 | $67.5 x $10^6$[c] |
| | Annualized cost | $67,000/year | $10.2 x $10^6$/year[c] |
| | Fine particle emissions | 138 lb/hr | 25,200 lb/hr[c] |
| IV. | 5% Opacity[e] | | |
| | Installed cost | $481,000 | $73.2 x $10^6$[c] |
| | Annualized cost | $74,000/year | $11.2 x $10^6$/year[c] |
| | Fine particle emissions | 67 lb/hr | 12,200 lb/hr[c] |

---

a/ Quantity emitted depends on control device installed.

b/ Control device required to meet standard is a fabric filter.

c/ Based on fact that approximately 17% of kilns are already equipped with fabric filter.

d/ Control device selected to meet standard is 98.7% efficient electrostatic precipitator.

e/ Control device selected to meet standard is 99.4% efficient electrostatic precipitator.

Table 25. INCREMENTAL ANNUALIZED COSTS FOR CEMENT KILNS TO MEET FINE PARTICLE EMISSION STANDARDS

| | | Annualized Cost ($/Year) | | Incremental Annualized Cost ($/Year) | |
|---|---|---|---|---|---|
| Emission Standard | Control System | Model Kiln | All Kilns | Model Kiln | All Kilns |
| 10% Opacity | 98.7% Efficient electrostatic precipitator | 67,000 | $10.2 \times 10^6$ | 67,000 | $10.2 \times 10^6$ |
| 5% Opacity | 99.4% Efficient electrostatic precipitator | 74,000 | $11.2 \times 10^6$ | 7,000 | $1 \times 10^6$ |
| All kilns install BICD | Fabric filter | 102,000 | $15.5 \times 10^6$ | 28,000 | $4.3 \times 10^6$ |

Reduction in fine particle emissions from all cement kilns that might be achieved by implementation of fine particle emission standards ranges from 72.5% for 10% opacity to 95.5% for the best installed control system.

Hot-mix Asphalt Plants - There are about 3,000 asphalt paving plants in the U.S. ranging in capacity from 75 to 300 tons/hr. A plant with a capacity of 150 tons/hr was selected as the basis for the estimates of control costs. Only the rotary dryer which is the major source of emissions was included in the cost estimates.

Tables 26 and 27 present the cost estimates for the rotary dryer. The opacity regulations are not as restrictive as the standard based on the utilization of the best installed control device--a fabric filter system. Currently, approximately 16% of the asphalt dryers are already equipped with fabric filters.

The installed costs for each standard, as shown in Table 26, reflect the fact that the opacity standards are not as restrictive as the best installed control system. However, the annualized costs for the opacity standards are higher than that for the best installed control system. Therefore, the choice of control equipment that might be installed to meet the opacity standards would depend on whether selection is based on installed cost or annualized cost.

Ferroalloy Furnaces - Three different types of furnaces are currently used to produce ferroalloy materials. Since the furnaces are quite different both with regard to their operation and emissions, individual models were used for each type of furnace. Tables 28 to 30 summarize the cost estimates for ferroalloy furnaces. Because of inadequate data on effluent characteristics from the individual furnaces, it was not possible to determine control equipment requirements for opacity regulations. As a result, only the costs associated with the standard based on the best installed control device are shown in Tables 28 to 30.

For the closed electric furnace, available data indicate that all existing furnaces are already equipped with the best installed control device. Currently only about 40% of the hooded open furnaces are equipped with the BICD (fabric filter), and installation of the BICD on all of this type of furnace would result in an 81% reduction in fine particle emissions. Approximately 20% of existing unhooded open furnaces are equipped with fabric filters, and installations of this device on all sources would reduce fine particle emissions by about 52.5%.

## Table 26. CONTROL EQUIPMENT COSTS FOR HOT-MIX ASPHALT PLANT ROTARY DRYERS

| | | Model Plant | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 150 tons/hr | $700 \times 10^{6}$ tons/year |
| | Production | 90,000 tons/year | $350 \times 10^{6}$ tons/year |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 840 lb/hr | $3.26 \times 10^{6}$ lb/hr |
| | (b) Present | _____[a] | 257,000 lb/hr |
| II. | Best installed control system[b] | | |
| | Installed cost | $53,000 | $\$173 \times 10^{6}$[c] |
| | Annualized cost | $10,600/year | $\$34.6 \times 10^{6}$/year[c] |
| | Fine particle emissions | 6.6 lb/hr | 25,600 lb/hr |
| III. | 10% Opacity[d] | | |
| | Installed cost | $21,500 | $\$28 \times 10^{6}$[e] |
| | Annualized cost | $19,800/year | $\$26 \times 10^{6}$/year[e] |
| | Fine particle emissions | 60 lb/hr | 200,000 lb/hr[e] |
| IV. | 5% Opacity[f] | | |
| | Installed cost | $29,700 | $\$97 \times 10^{6}$[g] |
| | Annualized cost | $29,700/year | $\$97 \times 10^{6}$/year[g] |
| | Fine particle emissions | 50 lb/hr | 167,000 lb/hr[g] |

---

[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is a fabric filter.

[c] Based on fact that approximately 16% of dryers are already equipped with fabric filters.

[d] Control device selected to meet standard is 94.8% efficient wet scrubber.

[e] Based on fact that approximately 16% of dryers are already equipped with fabric filters and assumption that 50% of the present cyclone plus wet scrubber systems will meet 10% opacity standard.

[f] Control device selected to meet standard is 97.4% efficient wet scrubber.

[g] Based on fact that approximately 16% of dryers are already with fabric filters and assumption that few of the existing cyclone plus wet scrubber systems will meet 5% opacity standard.

Table 27. INCREMENTAL ANNUALIZED COSTS FOR HOT-MIX ASPHALT PLANT ROTARY DRYERS TO MEET FINE PARTICLE EMISSION STANDARDS

| Emission Standard | Control System | Annualized Cost ($/Year) |  | Incremental Annualized Cost ($/Year) |  |
|---|---|---|---|---|---|
|  |  | Model Dryer | All Dryers | Model Dryer | All Dryers |
| 10% Opacity | 94.8% Efficient wet scrubber | 19,800 | $26 \times 10^6$ | 19,800 | $26 \times 10^6$ |
| 5% Opacity | 97.4% Efficient wet scrubber | 29,700 | $97 \times 10^6$ | 9,900 | $71 \times 10^6$ |
| All dryers install BICD | Fabric filter | 10,600 | $34.6 \times 10^6$ |  |  |

Table 28. CONTROL EQUIPMENT COSTS FOR FERROALLOY FURNACES (CLOSED ELECTRIC FURNACE)

| | Model Plant[a] | Industry Total |
|---|---|---|
| I. Source description | | |
| Capacity | 17,000 kw<br>(13,600 tons/year) | 1,025,000 kw<br>(820,000 tons/year) |
| Fine particle emissions | | |
| (a) Uncontrolled | 1,535 lb/hr | 92,000 lb/hr |
| (b) Present | ____[b] | 11,300 lb/hr[d] |
| II. Best installed control system[c] | | |
| Installed cost | $15,000 | ____[d] |
| Annualized cost | $3,000/year | ____[d] |
| Fine particle emission | 38 lb/hr | 11,300 lb/hr |

III. 10% Opacity - Insufficient effluent property data prohibited determination of control efficiency required.

IV. 5% Opacity - Same as 10% opacity.

---

a/ Operating hours - 8,000 hr/year

b/ Quantity emitted depends on control device installed.

c/ Control device required to meet standard is a disintegrator.

d/ MRI survey in 1970 indicated that all plants are already equipped with disintegrators.

## Table 29. CONTROL EQUIPMENT COSTS FOR FERROALLOY FURNACES (HOODED OPEN ELECTRIC FURNACE)

| | Model Plant[a] | Industry Total |
|---|---|---|
| I. Source description | | |
| Capacity | 13,500 kw<br>(10,800 tons/year) | 1,350,000 kw<br>(1,080,000 tons/year) |
| Fine particle emissions | | |
| (a) Uncontrolled | 1,295 lb/hr | 129,500 lb/hr |
| (b) Present | ______[b] | 84,100 lb/hr |
| II. Best installed control system[c] | | |
| Installed cost | $188,000 | $11.3 x $10^6$[d] |
| Annualized cost | $42,000/year | $2.5 x $10^6$/year[d] |
| Fine particle emissions | 158 lb/hr[e] | 15,800 lb/hr[e] |

III. 10% Opacity - Insufficient effluent property data prohibited determination of control efficiency required.

IV. 5% Opacity - Same as 10% opacity.

---

a/ Operating hours - 8,000 hr/year.

b/ Quantity emitted depends on control device installed.

c/ Control device required to meet standard is a fabric filter.

d/ Based on fact that approximately 40% of hooded electric furnaces are already equipped with fabric filter or disintegrator system.

e/ Based on assumed capture efficiency of hooding system of 90%.

Table 30. CONTROL EQUIPMENT COSTS FOR FERROALLOY FURNACE (UNHOODED OPEN FURNACE)

| | | Model Plant[a] | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 10,000 kw<br>(8,000 tons/year) | 750,000 kw<br>($6 \times 10^5$ tons/year) |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 960 lb/hr | 72,000 lb/hr |
| | (b) Present | ______[b] | 60,800 lb/hr |
| II. | Best installed control system[c] | | |
| | Installed cost | $750,000 | $\$45 \times 10^6$[e] |
| | Annualized cost | $168,000/year | $\$10.1 \times 10^6$/year[e] |
| | Fine particle emissions | 384 lb/hr[d] | 28,800 lb/hr[d] |
| III. | 10% Opacity - Insufficient effluent property data prohibited determination of control efficiency required. | | |
| IV. | 5% Opacity - Same as 10% opacity. | | |

---

[a] Operating hours - 8,000 hr/year.

[b] Quantity emitted depends on control device installed.

[c] Control device required to meet standard is a fabric filter.

[d] Based on assumed capture efficiency of hooding system of 80%.

[e] Based on fact that approximately 20% of open electric furnaces are already equipped with fabric filters.

Rotary Lime Kilns - Rotary lime kilns range in capacity from 50 to 560 tons/day. A kiln with a capacity of 250 tons/day was selected as the basis for the estimate of control costs. Only the rotary kiln, which is considered to be the major source of emissions from lime plants, was included in the cost estimates.

Tables 31 and 32 present the cost estimates for the rotary kilns. The opacity regulations are not as restrictive as the standard based on utilization of the best installed control device--a fabric filter.

The installed costs for each standard, as shown in Table 31, reflect the fact that the opacity standards are not as restrictive as that of the best installed control system. However, the annualized costs for the opacity standards are higher than that for the best installed control system. Therefore, the choice of control equipment that might be installed to meet the opacity standards would depend on whether selection is based on installed cost or annualized cost.

Municipal Incinerators - Individual furnaces used for municipal incineration range in size from 15 to 300 tons per 24 hr. An incinerator with a capacity of 10 tons/hr (240 tons/24 hr) was selected as the basis for the estimate of control costs.

Tables 33 and 34 present the cost estimate for municipal incineration. The opacity regulations are not as restrictive as the standard based on the use of the best installed control device--a 99.0% efficient electrostatic precipitator. Few incinerators in the U.S. are presently equipped with electrostatic precipitators but several are installing or planning to installed them.

Iron Foundry (Cupolas) - The cupola furnaces used in the iron foundry industry range in size from 1 ton/hr to 40 tons/hr or larger. A cupola with a capacity of 10 tons/hr was selected as the basis for the estimate of control costs.

Tables 35 and 36 present the cost estimates for the foundry cupolas. They also indicate that the opacity regulations are not as stringent as the standard based on equipping the foundry with the best installed control device (a fabric filter). However, the annualized costs for opacity standards are higher than that for the best installed system. Therefore, the choice of control equipment that might be installed to meet the opacity standards would depend on whether selection is based on installed cost or annualized cost.

Primary Aluminum-Electrolytic Cells - It is difficult to characterize the primary aluminum industry and the different sources and processes.

Table 31. CONTROL EQUIPMENT COSTS FOR ROTARY LIME KILNS

| | Model Plant | Industry Total |
|---|---|---|
| I. Source description | | |
| Capacity | 250 tons/day | 74,400 tons/day |
| Production | 87,500 tons/year | 18.5 x $10^6$ tons/year |
| Fine particle emissions | | |
| (a) Uncontrolled | 255 lb/hr | 75,800 lb/hr |
| (b) Present | ______[a] | 22,000 lb/hr |
| II. Best installed control system[b] | | |
| Installed cost | $70,000 | $12.6 x $10^6$[c] |
| Annualized cost | $14,000/year | $2.5 x $10^6$/year[c] |
| Fine particle emissions | 4.0 lb/hr | 1,200 lb/hr |
| III. 10% Opacity regulation[d] | | |
| Installed cost | $42,000 | $7.5 x $10^6$[e] |
| Annualized cost | $39,500/year | $7.1 x $10^6$/year[e] |
| Fine particle emissions | 56 lb/hr | 10,500 lb/hr[c] |
| IV. 5% Opacity regulation[f] | | |
| Installed cost | $58,000 | $10.4 x $10^6$[e] |
| Annualized cost | $60,500/year | $10.8 x $10^6$/year[e] |
| Fine particle emissions | 24 lb/hr | 4,800 lb/hr[c] |

---

[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is a fabric filter.

[c] Based on fact that approximately 40% of kiln capacity is already equipped with fabric filters.

[d] Control device selected to meet standard is 97.0% efficient wet scrubber.

[e] Based on 40% present application of fabric filters and assumption that only a few plants are equipped with wet scrubbers that meet the required efficiency.

[f] Control device selected to meet standard is 98.7% efficient wet scrubber.

Table 32. INCREMENTAL ANNUALIZED COSTS FOR ROTARY LIME KILNS TO MEET FINE PARTICLE EMISSION STANDARDS

| | | Annualized Cost ($/Year) | | Incremental Annualized Cost ($/Year) | |
|---|---|---|---|---|---|
| Emission Standard | Control System | Model Plant | All Plants | Model Plant | All Plants |
| All kilns install BICD | Fabric filter | 14,000 | $2.5 \times 10^6$ | 14,000 | $2.5 \times 10^6$ |
| 10% Opacity | 97.0% Efficient wet scrubber | 39,500 | $7.1 \times 10^6$ | 25,500 | $4.6 \times 10^6$ |
| 5% Opacity | 98.7% Efficient wet scrubber | 60,500 | $10.8 \times 10^6$ | 46,500 | $8.3 \times 10^6$ |

## Table 33. CONTROL EQUIPMENT COSTS FOR MUNICIPAL INCINERATORS

| | | Model Plant | Industry Total |
|---|---|---|---|
| I. | Source description | | |
| | Capacity | 10 tons/hr | 3,300 tons/hr |
| | Production | 80,000 tons/year | 18 x $10^6$ tons/year |
| | Fine particle emissions | | |
| | (a) Uncontrolled | 45.6 lb/hr | 15,000 lb/hr |
| | (b) Present | ______[a] | 13,100 lb/hr |
| II. | Best installed control system[b] | | |
| | Installed cost | $170,000 | $55.0 x $10^6$[c] |
| | Annualized cost | $27,000/year | $8.9 x $10^6$/year[c] |
| | Fine particle emissions | 1.5 lb/hr | 490 lb/hr |
| III. | 10% Opacity regulation[d] | | |
| | Installed cost | $116,000 | $38.0 x $10^6$[c] |
| | Annualized cost | $19,500/year | $6.4 x $10^6$/year[c] |
| | Fine particle emissions | 10.3 lb/hr | 3,400 lb/hr |
| IV. | 5% Opacity regulation[e] | | |
| | Installed cost | $136,000 | $45.0 x $10^6$[c] |
| | Annualized cost | $23,000/year | $7.6 x $10^6$/year[c] |
| | Fine particle emissions | 5.7 lb/hr | 1,900 lb/hr |

---

a/ Quantity emitted depends on control device installed.

b/ Control device required to meet standard is a 99.0% efficient electrostatic precipitator.

c/ Based on fact that few, if any, municipal incinerators are presently equipped with electrostatic precipitators.

d/ Control device selected to meet standard is 93.1% efficient electrostatic precipitator.

e/ Control device selected to meet standard is 96.2% efficient electrostatic precipitator.

Table 34. INCREMENTAL ANNUALIZED COSTS FOR MUNICIPAL INCINERATORS TO MEET FINE PARTICLE EMISSION STANDARDS

| | | Annualized Cost ($/Year) | | Incremental Annualized Cost ($/Year) | |
|---|---|---|---|---|---|
| Emission Standard | Control System | Model Plant | All Plants | Model Plant | All Plants |
| 10% Opacity | 93.1% Efficient electrostatic precipitator | 19,500 | $6.4 \times 10^6$ | 19,500 | $6.4 \times 10^6$ |
| 5% Opacity | 96.2% Efficient electrostatic precipitator | 23,000 | $7.6 \times 10^6$ | 3,500 | $1.2 \times 10^6$ |
| All incinerators install BICD | 99.0% Efficient electrostate precipitator | 27,000 | $8.9 \times 10^6$ | 7,500 | $2.5 \times 10^6$ |

## Table 35. CONTROL EQUIPMENT COSTS FOR IRON FOUNDRY CUPOLAS

| | Model Plant | Industry Total |
|---|---|---|
| I. Source description | | |
| Capacity | 10 tons/hr | Unknown |
| Production | 10,000 tons/year | 13.1 x $10^6$ tons/year |
| Fine particle emissions | | |
| (a) Uncontrolled | 17.5 lb/hr | 22,900 lb/hr |
| (b) Present | ____[a] | 13,100 lb/hr |
| II. Best installed control system[b] | | |
| Installed cost | $60,400 | $79.1 x $10^6$[c] |
| Annualized cost | $12,100/year | $15.8 x $10^6$/year[c] |
| Fine particle emissions | 0.27 lb/hr | 356 lb/hr |
| III. 10% Opacity regulation[d] | | |
| Installed cost | $27,600 | $36.2 x $10^6$[e] |
| Annualized cost | $22,400/year | $29.4 x $10^6$/year[e] |
| Fine particle emissions | 4.5 lb/hr | 5,900 lb/hr |
| IV. 5% Opacity regulation[f] | | |
| Installed cost | $34,500 | $45.2 x $10^6$[e] |
| Annualized cost | $32,800/year | $43.0 x $10^6$/year[e] |
| Fine particle emissions | 3.0 lb/hr | 4,000 lb/hr |

---

[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is a fabric filter.

[c] Based on the fact that only a small percentage (< 5%) of cupolas are now equipped with fabric filters.

[d] Control device selected to meet standard is 94.2% efficient wet scrubber.

[e] Based on information indicating that few plants are equipped with control devices that meet the required efficiency.

[f] Control device selected to meet standard is 97.1% efficient wet scrubber.

Table 36. INCREMENTAL ANNUALIZED COSTS FOR IRON FOUNDRY CUPOLAS TO MEET FINE PARTICLE EMISSION STANDARDS

| | | Annualized Cost ($/Year) | | Incremental Annualized Cost ($/Year) | |
|---|---|---|---|---|---|
| Emission Standard | Control System | Model Plant | All Plants | Model Plant | All Plants |
| All cupolas install BICD | Fabric filter | 12,100 | $15.8 \times 10^6$ | 12,100 | $15.8 \times 10^6$ |
| 10% Opacity | 94.2% Efficient wet scrubber | 22,400 | $29.4 \times 10^6$ | 10,300 | $13.6 \times 10^6$ |
| 5% Opacity | 97.1% Efficient wet scrubber | 32,800 | $43.0 \times 10^6$ | 20,700 | $27.2 \times 10^6$ |

However, the electrolytic cells are one of the major particulate sources within the industry and are the only ones on which enough information was available to attempt estimation of costs for the emission standards considered in this program.

Primary aluminum plants may range in size from 150 to 700 tons/day, but these usually consist of several "potlines" with each potline made up of several hundred cells. Information obtained in the study indicated 15 cells might be ducted to the same control device. Therefore, a 15-cell potline producing an estimated 3,000 tons/year of aluminum was selected as the basis for the estimate of control costs.

Table 37 presents the cost estimates for the best installed control system. The Alcoa 398 process was used as the best installed system, and it was assumed to be equivalent to a fabric filter for cost purposes. However, the capture efficiency for the associated hooding systems was assumed to be 95%.

Information was not available on characteristics of the effluent from the electrolytic cells that would permit estimation of control device efficiencies required to meet the opacity standards.

Primary Copper - In the U.S., 14 smelters represent 98% of the U.S. capacity and these range in size from 48 tons/day up to 1,000 tons/day. The configuration of these smelters is quite varied. A 230 ton/day smelter was selected as the basis for this study to estimate the particulate control costs. Although a significant number of these plants may have equipped some sources with $SO_2$ removal or recovery processes, the costs of these processes and emissions from them have not been considered.

The 230 ton/day model plant consisted of one roaster, one reverberatory furnace, and two convertors. It was assumed that two identical control devices would be installed to control emission from the above sources and that the average particle size distribution was 25% < 3 μ.

Table 38 presents the cost estimates for the best installed control system--assumed to be a 99.7% efficient electrostatic precipitator. It was also assumed that none of the plants are now equipped with control systems (or $SO_2$ removal processes) that would meet the required efficiency of 99.7%.

Information was not available on characteristics of the effluents that would permit estimation of control device efficiencies required to meet the opacity standards.

Table 37. CONTROL EQUIPMENT COSTS FOR PRIMARY ALUMINUM-ELECTROLYTIC CELLS

| | Model Plant | Industry Total |
|---|---|---|
| I. Source description<br>One potline (15 cells) | | |
| Production | 3,000 tons/year | 4.0 x $10^6$ tons/year |
| Fine particle emissions | | |
| (a) Uncontrolled | 29.1 lb/hr | 48,500 lb/hr |
| (b) Present | ______[a] | 16,200 lb/hr |
| II. Best installed control system[b] | | |
| Installed cost | $71,200 | $95.0 x $10^6$[c] |
| Annualized cost | $16,000/year | $21.3 x $10^6$/year[c] |
| Fine particle emissions | 1.5 lb/hr | 2,000 lb/hr |

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[a] Quantity emitted depends on control device installed.

[b] Control device required to meet standard is the Alcoa 398 control system, which was considered equivalent to a fabric filter for estimation purposes.

[c] Based on fact that few plants are now equipped with the specified control device.

[d] Emissions based on estimated capture efficiency of 95%.

Table 38. CONTROL EQUIPMENT COSTS FOR PRIMARY COPPER PLANTS

| | Model Plant | Industry Total |
|---|---|---|
| I. Source Description | | |
| Production | 76,000 tons/year | 1.7 x $10^6$ tons/year |
| Fine particle emissions | | |
| (a) Uncontrolled | 1,450 lb/hr[a] | 32,400 lb/hr[a] |
| (b) Present | [b] | 7,400 lb/hr[a] |
| II. Best installed control system[c] | | |
| Installed cost | $532,000 | $11.9 x $10^6$[d] |
| Annualized cost | $84,000/year | $1.9 x $10^6$/year[d] |
| Fine particle emissions | 16.7 lb/hr[a] | 374 lb/hr[a] |

---

[a] Emissions based on assumption that uncontrolled particle size is 25% < 3 μ.

[b] Quantity emitted depends on control device installed.

[c] Control device selected to meet standard is 99.7% efficient electrostatic precipitator. $SO_2$ removal process costs and emissions have not been considered.

[d] Costs are based on assumption that plants are not now equipped with control that would meet the required efficiency (99.7%).

## ESTIMATED REDUCTIONS IN FINE PARTICLE EMISSIONS

Implementation of emission standards based on particle size can achieve significant reductions in the fine particulate burden entering the atmosphere from stationary sources. The extent of the reduction depends upon the type(s) of emission standards that are selected for implementation. Table 39 presents a summary of estimated reductions in fine particle emissions from selected industrial sources which might result from the implementation of the opacity or BICD emission standards. The time required to achieve the installation of requisite control equipment on all the sources of fine particulate pollutants is difficult to determine. If one assumes that fine particle emission standards are proposed, adopted, and implemented in the 1975-1980 period, then it seems reasonable to assume that total compliance could be achieved by 1985.

The emission figures presented in Table 39 are based on current production rates. Production rates have generally increased for industrial sources as a function of time. Changes in production rates must be included in calculations when an attempt is made to estimate fine particle emission levels which may result from control efforts in future years. As a part of a previous study, MRI made projections of fine particle emissions using two different methods.[61/] Table 40 presents the results of these projections for the same group of sources listed in Table 39.

The projection of emissions by Method I assumed that there would be no change in the net control for a source. This assumption results in an increase in emissions in proportion to increases in production capacity. Production figures were projected by the same methods outlined in Ref. 92 and were used to proportionally increase the current mass of fine particle emissions.

Method II takes into account the increase in production, but two assumptions are also made:

1. All sources would be controlled by 1980, i.e., application of control will reach 100% by 1980.

2. Increased utilization of the most efficient control devices would continuously increase the efficiency of control on fine particles so that by the year 2000 it would be equivalent to controlling all sources with fabric filters. The fabric filter was selected as a reference standard of performance because it is one of the most efficient devices currently available for collecting fine particulates. It seems realistic to assume that improvements in the other control devices and possible

Table 39. ESTIMATES OF FINE PARTICLE EMISSIONS AS A FUNCTION OF EMISSION STANDARD

| | Estimated Fine Particle Emissions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Uncontrolled | | Present | | BICD Standard[b] | | 10% Opacity Standard | | 5% Opacity Standard | |
| Source | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year | Lb/Hr | Ton/Year |
| I. Coal combustion | 796,000 | 3,184,000 | 243,000 | 972,000 | 15,000 | 60,000 | 5,050 | 20,200 | 2,510 | 10,040 |
| II. Iron and steel | | | | | | | | | | |
| A. Sinter machines | 7,100 | 28,400 | 1,400 | 5,600 | 64 | 256 | 722 | 2,888 | 354 | 1,416 |
| B. Basic oxygen furnace | 400,000 | 1,600,000 | 43,600 | 174,400 | 2,560 | 10,240 | 1,540 | 6,160 | 800 | 3,200 |
| C. Electric arc furnace | 27,400 | 109,600 | 3,600 | 14,400 | 645 | 2,580 | 1,036 | 4,144 | 683 | 2,732 |
| III. Cement plants, rotary kilns | 243,000 | 972,000 | 44,300 | 177,200 | 2,000 | 8,000 | 25,200 | 100,800 | 12,200 | 48,800 |
| IV. Asphalt plants, dryers | 3,260,000 | 1,956,000 | 257,000 | 154,200 | 25,600 | 15,360 | 200,000 | 120,000 | 167,000 | 100,200 |
| V. Ferroalloy plants | | | | | | | | | | |
| A. Closed electric furnace | 92,000 | 368,000 | 11,300 | 45,200 | 11,300 | 45,200 | NC[a] | NC | NC | NC |
| B. Hooded open electric furnace | 129,500 | 518,000 | 84,100 | 336,400 | 15,800 | 63,200 | NC | NC | NC | NC |
| C. Unhooded open electric furnace | 72,000 | 288,000 | 60,800 | 243,200 | 28,800 | 115,200 | NC | NC | NC | NC |
| VI. Lime plants, rotary kilns | 75,800 | 303,200 | 22,000 | 88,000 | 1,200 | 4,800 | 10,500 | 42,000 | 4,800 | 19,200 |
| VII. Municipal incinerators | 15,000 | 37,500 | 13,100 | 32,800 | 490 | 1,225 | 3,400 | 8,500 | 1,900 | 4,750 |
| VIII. Iron foundry, cupola | 22,900 | 22,900 | 13,100 | 13,100 | 356 | 356 | 5,900 | 5,900 | 4,000 | 4,000 |

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a/ Not calculated.

b/ BICD - Best installed control device (not necessarily the highest efficiency device available, but rather the best that is generally being installed at present time).

Table 40. PROJECTIONS OF FINE PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES
($10^6$ Tons/Year)

| | | Year | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Source | Method | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 |
| 1. Stationary combustion | | | | | | | | |
| A. Coal | | | | | | | | |
| 1. Electric utility | I | 1.046 | 1.201 | 1.374 | 1.600 | 1.864 | 2.110 | 2.388 |
| | II | 0.976 | 0.883 | 0.731 | 0.653 | 0.528 | 0.335 | 0.090 |
| 2. Industrial | I | 0.133 | 0.150 | 0.170 | 0.170 | 0.170 | 0.166 | 0.164 |
| | II | 0.127 | 0.111 | 0.084 | 0.064 | 0.043 | 0.023 | 0.002 |
| 2. Iron and steel | | | | | | | | |
| A. Sinter machines | I | 0.006 | 0.007 | 0.008 | 0.009 | 0.009 | 0.010 | 0.010 |
| | II | 0.006 | 0.006 | 0.005 | 0.004 | 0.003 | 0.002 | 0.000 |
| B. Basic oxygen furnace | I | 0.188 | 0.293 | 0.454 | 0.515 | 0.581 | 0.618 | 0.654 |
| | II | 0.177 | 0.235 | 0.305 | 0.277 | 0.237 | 0.170 | 0.094 |
| C. Electric arc furnace | I | 0.015 | 0.018 | 0.021 | 0.023 | 0.026 | 0.029 | 0.034 |
| | II | 0.014 | 0.010 | 0.004 | 0.004 | 0.004 | 0.003 | 0.003 |
| 3. Cement plants, rotary kilns | I | 0.188 | 0.227 | 0.273 | 0.319 | 0.372 | 0.421 | 0.476 |
| | II | 0.175 | 0.164 | 0.140 | 0.125 | 0.101 | 0.062 | 0.016 |
| 4. Hot mix asphalt plants, dryers | I | 0.168 | 0.205 | 0.250 | 0.305 | 0.375 | 0.460 | 0.563 |
| | II | 0.158 | 0.158 | 0.152 | 0.141 | 0.117 | 0.074 | 0.018 |
| 5. Ferroalloy electric furnaces | I | 0.155 | 0.166 | 0.180 | 0.198 | 0.219 | 0.241 | 0.267 |
| | II | 0.131 | 0.074 | 0.008 | 0.009 | 0.010 | 0.011 | 0.012 |
| 6. Lime plants, rotary kilns | I | 0.103 | 0.134 | 0.174 | 0.189 | 0.206 | 0.311 | 0.466 |
| | II | 0.095 | 0.094 | 0.086 | 0.071 | 0.053 | 0.044 | 0.016 |
| 7. Municipal incinerators | I | 0.040 | 0.051 | 0.061 | 0.071 | 0.081 | 0.095 | 0.109 |
| | II | 0.037 | 0.037 | 0.031 | 0.027 | 0.021 | 0.014 | 0.003 |
| 8. Iron foundries, cupolas | I | 0.013 | 0.015 | 0.016 | 0.017 | 0.017 | 0.018 | 0.019 |
| | II | 0.012 | 0.010 | 0.006 | 0.005 | 0.003 | 0.002 | 0.003 |

development of new devices would allow the efficiency of control devices, in the year 2000, to match the performance capability of the best devices that are presently available. Details and examples of the calculations for both methods are given in Ref. 61.

The two projection methods represent two extremes: no improvement in control versus stringent control. An intermediate position is more probable, but projection of an intermediate situation requires information regarding the percent application of each type of control device on specific sources in the future years. Of course, this information is not available, and to project emissions, gross assumptions would have to be made regarding future equipment utilization.

## ECONOMIC IMPACT OF FINE PARTICLE EMISSION STANDARDS ON SELECTED SOURCES

A detailed economic evaluation of the economic impacts of emission standards involves far more than simply making cost, revenue and capital projections over a specified time period. A thorough feasibility analysis must give careful attention to how all the different parts fit together and react with each other, in much the same way as a critical path analysis describes the interactions among all the activities in a complex construction project.

Just as in a natural ecosystem, many of the elements in the economic system are closely interrelated, even though--just as in the ecosystem--the interrelationships may not be instantly obvious, and even when they are, they may be hard to express in quantitative or absolute terms.

The accompanying illustration (Figure 19) shows, in a general sense, some of the major microeconomic factors that should be considered in the economic analysis of the impacts of air quality control programs on a given firm or industry.

Air pollution control standards will primarily influence unit costs. Unit costs include both variable and fixed elements. The variable costs, consisting mainly of labor and materials, are related to volume; any change in volume is accompanied by a proportionate change in the direct costs. Fixed costs, consisting mainly of capital-related charges and overhead expenses, are primarily related to the amount of capital invested in the operation and remain constant over a wide range of operating conditions. In total, unit costs generally decline as volume increases, as the fixed costs are spread over a broader base. The imposition of air pollution control standards will affect the firm's costs of production by increasing its capital investment requirements, and by raising its direct manufacturing

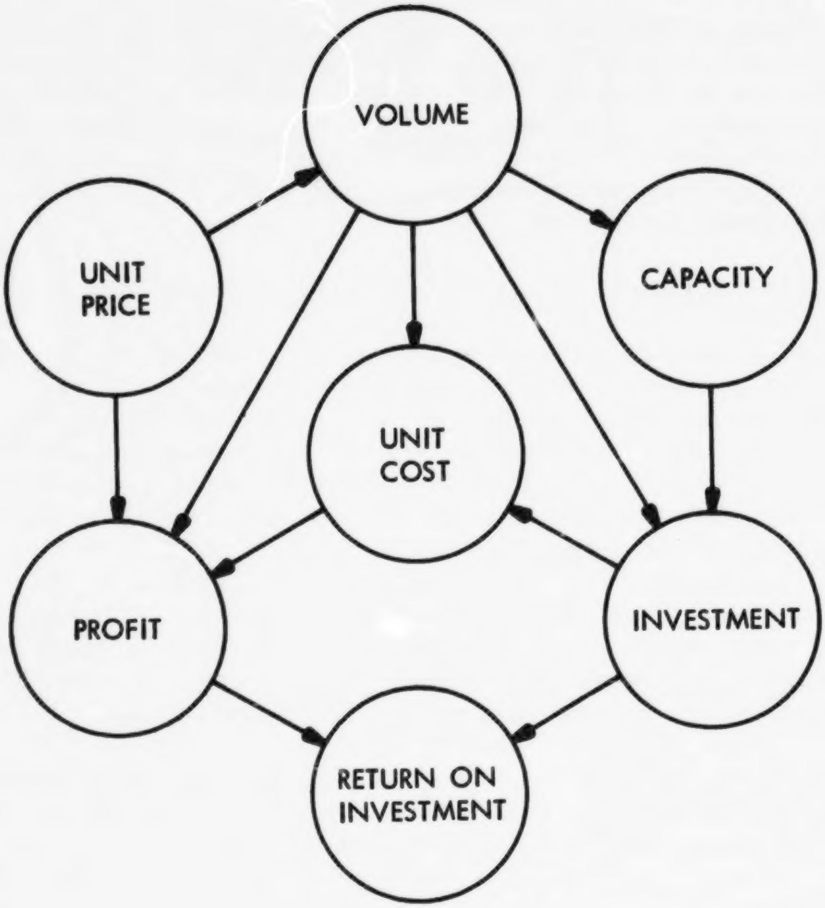
VOLUME
UNIT PRICE
CAPACITY
UNIT COST
PROFIT
INVESTMENT
RETURN ON INVESTMENT

Figure 19. Interrelationships among factors affecting the economics of a firm

costs by whatever amount is required to operate and maintain the new air pollution control facilities.

Figure 20 illustrates a possible structure for analyzing the economic impact of new air pollution control requirements on a specific firm. The specified control efficiency and plant size (as reflected by its production volume) dictate the size and type of control equipment needed, which in turn determine the capital and operating costs associated with the control program.

The total cost of control represents an incremental cost of production, which can either be absorbed by the firm or passed on to its consumers by means of increased prices. Should prices be increased, however, sales are likely to decrease; if costs are absorbed, volume may remain constant, but profit margins will suffer. Regardless of the economic impact on the firm, then, its way of doing business will be affected.

Table 41 shows an example of the economic impact of air pollution control requirements on an electric generating plant, as reflected in its costs of power production. Again, the control efficiency determines the control cost, which results in higher costs of energy production, ultimately to be passed along to the consumer. As is evident from the control costs shown in Table 41, control becomes increasingly expensive as the efficiency requirements increase. This is particularly significant in certain industries, where any price increase will cause a major decline in sales, with customers either cutting back on their consumption, shifting to other producers, or substituting other products.

An in-depth analysis of the economic impact of fine particle emission standards on individual industry segments was outside the scope of this study. The economic impact analysis conducted during this program was confined to the determination of the increase in production costs for specific industries. An example of the procedures used to calculate the increase in production costs associated with the fine particle emission standards is presented in the next section.

## Example of Calculation of Economic Impact

The financial and operating characteristics of a typical coal-fired steam-electric generating plant were developed to use as a model for determining the economic effects of different control strategies for fine particulates.

Based on the compiled statistics of privately owned electric utilities in the United States, generating costs are equally divided between capital charges and production expenses, with capital charges averaging 15% of

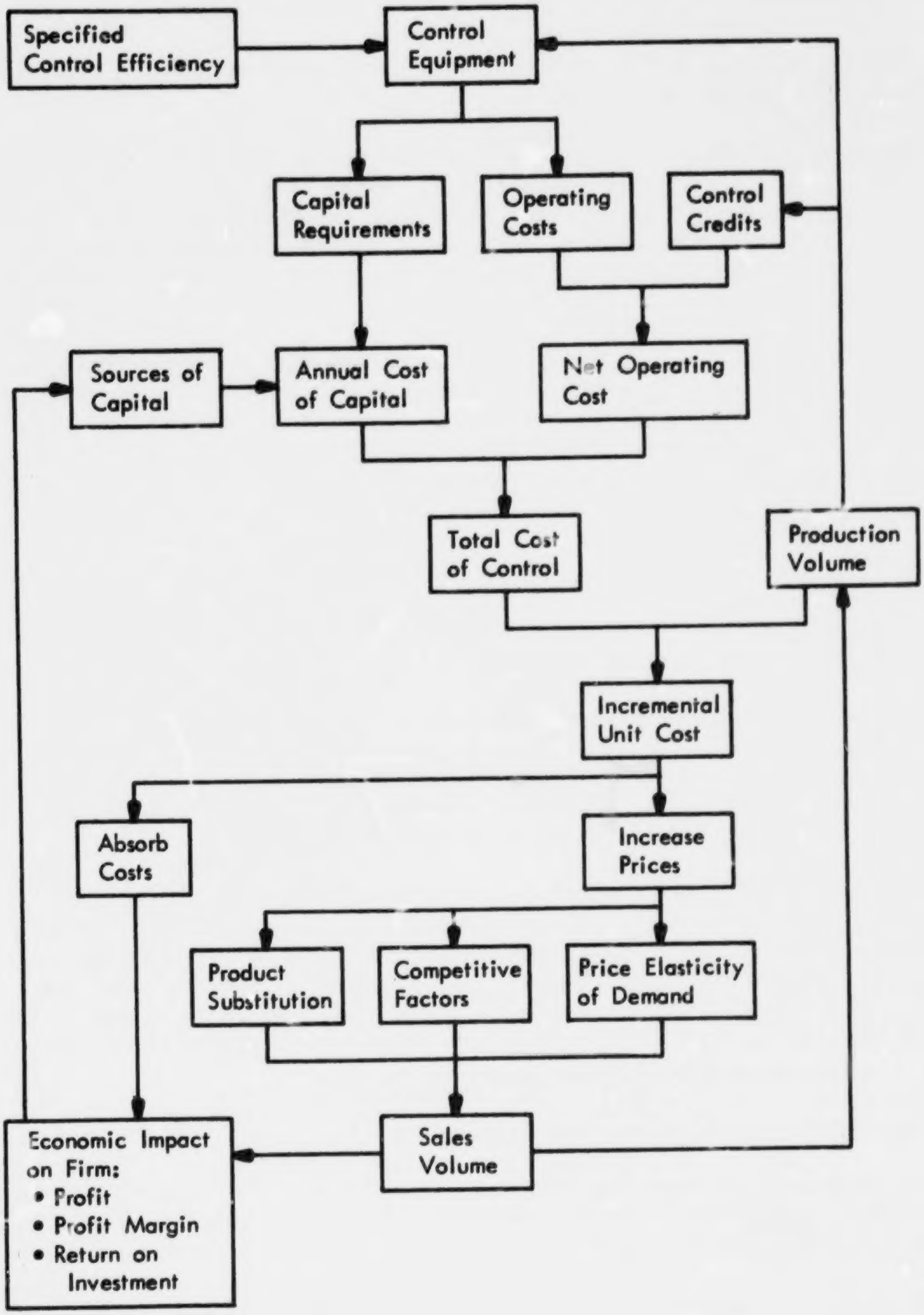
Specified Control Efficiency
Control Equipment
Capital Requirements
Operating Costs
Control Credits
Sources of Capital
Annual Cost of Capital
Net Operating Cost
Total Cost of Control
Production Volume
Incremental Unit Cost
Absorb Costs
Increase Prices
Product Substitution
Competitive Factors
Price Elasticity of Demand
Economic Impact on Firm:
• Profit
• Profit Margin
• Return on Investment
Sales Volume

Figure 20. Structure for microeconomic impact analysis

Table 41. EXAMPLE OF ECONOMIC IMPACT OF AIR POLLUTION CONTROL REQUIREMENTS ON ELECTRIC POWER GENERATING COSTS

| Control Method | Control Efficiency (%) | Total Annual Cost ($1,000) | | | Net Cost (¢/kwh) | Incremental Cost (¢/kwh) |
|---|---|---|---|---|---|---|
| | | Electric Production | Pollution Control | Total | | |
| None | 0 | 9,010 | 0 | 9,010 | 0.935 | -- |
| Louver | 58.6 | 9,010 | 100 | 9,110 | 0.945 | 0.010 |
| Medium efficiency cyclone | 65.3 | 9,010 | 96 | 9,106 | 0.945 | 0.000 |
| High efficiency cyclone | 84.2 | 9,010 | 156 | 9,166 | 0.951 | 0.006 |
| Multiple cyclones | 93.8 | 9,010 | 168 | 9,178 | 0.952 | 0.001 |
| Electrostatic precipitator | 99.0 | 9,010 | 602 | 9,612 | 0.997 | 0.045 |
| Fabric filter | 99.7 | 9,010 | 852 | 9,862 | 1.023 | 0.026 |
| Fabric filter | 99.8 | 9,010 | 1,008 | 10,018 | 1.039 | 0.016 |
| Fabric filter | 99.9 | 9,010 | 1,190 | 10,200 | 1.058 | 0.019 |

the utilities net plant investment. Table 42 summarizes the pertinent financial characteristics of the 400-MW model steam generating plant burning 1.2 million tons of coal annually to produce 2.4 billion kilowatt-hours of electric energy.

As shown in Table 42 the total annual cost of service for this typical plant comes to $36 million, or $0.015/kwh of net generation, exclusive of emission control equipment.

Virtually any desired level of particulate emission control can be achieved at a price. Table 43 shows the estimated control costs associated with various control efficiencies, ranging from the best installed control device (BICD), an electrostatic precipitator with 99.0% efficiency to 99.9% efficiency, and including the 10% opacity level (99.66% collection efficiency) and the 5% opacity level (99.83% efficiency).

Estimated annual control costs vary from $241,500 at the 99.0% efficiency level to $465,000 at 99.9% efficiency. Here, annual charges are estimated at 15.0% of the total installed cost of the control equipment, the same rate applied to the utility's other plant facilities. This, it should be pointed out, is the lowest capital charge rate that would conceivably apply to the control equipment, and a rate in the 17 to 20% range is likely to be applied to this type of air pollution control equipment.

At control efficiencies in the 99.0 to 99.9% range and with capital charges computed at 15% of installed equipment costs, the total impact of air pollution control costs on the net cost of electric generation is almost negligible, as shown in Table 44. Here it can be seen that net costs per kilowatt-hour ($0.015 without emission controls) increase only to $0.0152 even at the 99.9% control level. At 10% opacity, total control costs amount to just $0.00013/kwh, and at 5% opacity they increase only to $0.00016/kwh.

Thus, the net cost difference between zero control and control at the 5% opacity (or 99.83% efficiency) level amounts to an increase of 1.3% in terms of the cost of generating electrical energy under the prescribed conditions. By way of comparison, O'Connor and Citarella reported that the total annual cost of particulate air pollution for a 600-MW steam-electric plant ranges from 0.7 to 2.0% of the total annual cost of power.[89]

## Control Costs in Selected Industries

The costs of fine particulate control associated with appropriate control levels--BICD or specified opacity levels--have been estimated for the industries representing the main sources of fine particulate emissions.

## Table 42. TYPICAL FINANCIAL CHARACTERISTICS OF 400-MW ELECTRIC GENERATING PLANT[a]

| | |
|---|---|
| Net plant investment at \$300/kw | \$120,000,000 |
| Operating revenues at \$0.015/kwh | 36,000,000 |
| Operating expenses | |
| Fuel - $1.2 \times 10^6$ tons at \$7.00/ton | 8,400,000 |
| Other production expenses at \$0.004/kwh | 9,600,000 |
| Total operating expenses | 18,000,000 |
| Capital charges[b] at 15% of plant investment | 18,000,000 |
| Total cost of service | \$ 36,000,000 |

---

a/ Net annual generation = $2.4 \times 10^9$ kwh; load factor = 68.5%.

b/ Includes depreciation, interest, A&G expenses, ad valorem and income taxes, and return on investment.

Table 43. ESTIMATED CONTROL COSTS FOR 400-MW ELECTRIC GENERATING PLANT

| Emissions Controlled (%) | Emissions Uncontrolled (%) | Installed Cost of Control Equipment ($) | Annual Operating and Maintenance Cost ($) | Annual Capital Charges ($) | Total Annual Control Cost ($) |
|---|---|---|---|---|---|
| 99.00 | 1.00 | 1,030,000 | 87,000 | 154,500 | 241,500 |
| 99.50 | 0.50 | 1,280,000 | 100,000 | 192,000 | 292,000 |
| 99.60 | 0.40 | 1,355,000 | 105,000 | 203,250 | 308,250 |
| 99.66 | 0.34 | 1,400,000 | 110,000 | 210,000 | 320,000 |
| 99.70 | 0.30 | 1,430,000 | 114,000 | 214,500 | 328,500 |
| 99.80 | 0.20 | 1,530,000 | 132,000 | 229,500 | 361,500 |
| 99.83 | 0.17 | 1,570,000 | 143,000 | 235,500 | 378,500 |
| 99.90 | 0.10 | 1,670,000 | 215,000 | 250,500 | 465,500 |

Table 44. EFFECT OF CONTROL COSTS ON COST OF ELECTRIC POWER

| Emissions Controlled (%) | Total Cost of Power Generation ($/Year) | Total Annual Control Cost ($) | Total Annual Cost ($) | Cost/kwh ($) |
|---|---|---|---|---|
| No control | 36,000,000 | 0 | 36,000,000 | 0.01500 |
| 99.00[a] | 36,000,000 | 241,500 | 36,241,500 | 0.01510 |
| 99.50 | 36,000,000 | 292,000 | 36,292,000 | 0.01512 |
| 99.60 | 36,000,000 | 308,250 | 36,308,250 | 0.01513 |
| 99.66[b] | 36,000,000 | 320,000 | 36,320,000 | 0.01513 |
| 99.70 | 36,000,000 | 328,500 | 36,328,500 | 0.01514 |
| 99.80 | 36,000,000 | 361,500 | 36,361,500 | 0.01515 |
| 99.83[c] | 36,000,000 | 378,500 | 36,378,500 | 0.01516 |
| 99.90 | 36,000,000 | 465,500 | 36,465,500 | 0.01519 |

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[a] BICD.

[b] 10% opacity.

[c] 5% opacity.

Capital charges have been computed at four different levels, thus encompassing the entire range of possibilities for a given plant. The specific levels selected represent the minimum depreciable life established by the Internal Revenue Service for approved pollution abatement equipment; the maximum expected useful service life of typical combustion equipment for which control facilities are required; and two intermediate values, reflecting the probable economic life ranges of the particulate control devices being installed.

The four capital charge rates used in converting the installed cost of particulate control systems to an equivalent annual amount are made up as follows:

| Economic Life Year | Straight-Line Depreciation Rate (%) | Average Interest at 8% | Other Capital Related Expenses (%) | Total Annual Capital Charge Rate (%) |
|---|---|---|---|---|
| 5 | 20 | 5 | 5 | 30 |
| 10 | 10 | 5 | 5 | 20 |
| 15 | 7 | 5 | 5 | 17 |
| 20 | 5 | 5 | 5 | 15 |

The average interest is computed at 8% of the undepreciated account balance, and, added to the straight-line depreciation rate, constitutes the "capital recovery rate" used to amortize an investment over a specified time period. Other capital-related expenses include insurance costs, ad valorem taxes, and administrative expenses.

Total annual costs, including both capital charges and direct operating expenses, were computed for each model plant, at selected control levels, for each capital charge rate. These annual costs were then related to the model plant's production rate, resulting in a net annual control cost per unit of production. This amount, related to the value of the end product, provides a realistic measure of the economic impact of a given control strategy under the prescribed conditions.

Table 45 summarizes the estimated total annual control costs for model plants in selected industries. Estimated costs are presented for the BICD, 10% opacity and 5% opacity emission standards. Table 46 presents the estimated costs associated with the BICD standard for both the model plants and the total industry.

Table 45. EFFECT OF CONTROL CRITERIA ON CONTROL COSTS IN SELECTED INDUSTRIES

| Source | Control Criteria | Fine Particle Control Efficiency (%) | Model Plant Annual Production Rate | Total Annual Control Cost ($1,000) at Specified Capital Charge Rate 0.15 | 0.17 | 0.20 | 0.30 |
|---|---|---|---|---|---|---|---|
| Coal-fired electric plant | BICD | 98.13 | 2.4 x $10^9$ kwh | 241.5 | 262.1 | 293.0 | 396.0 |
| | 10% Opacity | 99.36 | | 320.0 | 348.0 | 390.0 | 530.0 |
| | 5% Opacity | 99.68 | | 378.5 | 409.9 | 457.0 | 614.0 |
| Municipal incinerator | BICD | 96.71 | 80,000 tons | 35.5 | 38.9 | 44.0 | 61.0 |
| | 10% Opacity | 77.41 | | 25.3 | 27.6 | 31.1 | 42.7 |
| | 5% Opacity | 87.50 | | 29.8 | 32.5 | 36.6 | 50.2 |
| Cement plant (rotary kiln) | BICD | 99.17 | 3.0 x $10^6$ bbls | 125.1 | 134.3 | 148.2 | 194.4 |
| | 10% Opacity | 89.58 | | 89.2 | 98.1 | 111.4 | 155.9 |
| | 5% Opacity | 94.94 | | 98.1 | 107.7 | 122.1 | 170.2 |
| Asphalt plant (rotary dryers) | BICD | 99.21 | 90,000 tons | 13.3 | 14.3 | 15.9 | 21.2 |
| | 10% Opacity | 92.86 | | 20.9 | 21.3 | 22.0 | 24.1 |
| | 5% Opacity | 94.05 | | 31.2 | 31.8 | 32.7 | 35.6 |
| Iron and steel | | | | | | | |
| (a) Basic oxygen furnace | BICD | 99.70 | 1.0 x $10^6$ tons | 211.0 | 230.2 | 259.0 | 355.0 |
| | 10% Opacity | 99.82 | | 227.0 | 247.0 | 277.0 | 377.0 |
| | 5% Opacity | 99.91 | | 255.0 | 274.2 | 303.0 | 399.0 |
| (b) Electric arc furnace | BICD | 97.64 | 100,000 tons | 50.1 | 53.7 | 59.2 | 77.4 |
| | 10% Opacity | 93.54 | | 36.1 | 39.3 | 44.1 | 60.2 |
| | 5% Opacity | 97.24 | | 42.2 | 46.3 | 52.4 | 72.8 |
| (c) Sintering (windbox) | BICD | 99.10 | 1.46 x $10^6$ tons | 277.0 | 297.0 | 327.0 | 427.0 |
| | 10% Opacity | 87.76 | | 184.5 | 199.9 | 223.0 | 300.0 |
| | 5% Opacity | 94.05 | | 204.5 | 221.5 | 247.0 | 332.0 |
| Lime plant (rotary kiln) | BICD | 98.43 | 87,500 tons | 17.5 | 18.9 | 21.0 | 28.0 |
| | 10% Opacity | 78.04 | | 41.6 | 42.4 | 43.7 | 47.9 |
| | 5% Opacity | 90.59 | | 63.4 | 64.6 | 66.3 | 72.1 |
| Iron foundry cupola | BICD | 98.46 | 10,000 tons | 15.1 | 16.3 | 18.1 | 24.2 |
| | 10% Opacity | 74.29 | | 23.8 | 24.3 | 25.2 | 27.9 |
| | 5% Opacity | 82.86 | | 34.5 | 35.2 | 36.3 | 39.7 |

Table 46. TOTAL ANNUAL COST OF ACHIEVING BICD[a]-LEVEL CONTROL OF FINE PARTICULATES IN SELECTED INDUSTRIES

| Source | Model Plant Production Rate/Year | Total Annual Control Cost for Model Plant at Specified Capital Charge Rate ($1,000) | | | | Total Annual Industry Production | Total Annual Control Cost for Industry at Specified Capital Charge Rate ($$10^6$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.15 | 0.17 | 0.20 | 0.30 | | 0.15 | 0.17 | 0.20 | 0.30 |
| Coal-fired electric plant | 2.4 x $10^9$ kwh | 241.5 | 262.1 | 293.0 | 396.0 | 516 x $10^9$ kwh | 51.9 | 56.4 | 63.0 | 85.1 |
| Municipal incinerator | 80,000 tons | 35.5 | 38.9 | 44.0 | 61.0 | 18 x $10^6$ tons | 8.0 | 8.8 | 9.9 | 13.7 |
| Cement plant (rotary kiln) | 3.0 x $10^6$ bbls | 125.1 | 134.3 | 148.2 | 194.4 | 400 x $10^6$ bbls | 16.7 | 17.9 | 19.8 | 25.9 |
| Asphalt plant (rotary dryers) | 90,000 tons | 13.3 | 14.3 | 15.9 | 21.2 | 350 x $10^6$ tons | 51.7 | 55.6 | 61.8 | 82.4 |
| Iron and steel | | | | | | | | | | |
| (a) Basic oxygen furnace | 1.0 x $10^6$ tons | 211.0 | 230.2 | 259.0 | 355.0 | 50 x $10^6$ tons | 10.6 | 11.5 | 13.0 | 17.8 |
| (b) Electric arc furnace | 100,000 tons | 50.1 | 53.7 | 59.2 | 77.4 | 21.5 x $10^6$ tons | 10.8 | 11.5 | 12.7 | 16.6 |
| (c) Sintering (windbox) | 1.46 x $10^6$ tons | 277.0 | 297.0 | 327.0 | 427.0 | 54 x $10^6$ tons | 10.2 | 11.0 | 12.1 | 15.8 |
| Ferroalloy | | | | | | | | | | |
| (a) Unhooded open electric furnace | 8,000 tons | 205.5 | 220.5 | 243.0 | 318.0 | 600,000 tons | 15.4 | 16.5 | 18.2 | 23.9 |
| (b) Hooded open electric furnace | 10,800 tons | 51.4 | 55.2 | 60.8 | 79.6 | 1.08 x $10^6$ tons | 5.1 | 5.5 | 6.1 | 8.0 |
| (c) Closed electric furnace | 13,600 tons | 3.8 | 4.1 | 4.5 | 6.0 | 820,000 tons | 0.2 | 0.2 | 0.3 | 0.4 |
| Lime plant (rotary kiln) | 87,500 tons | 17.5 | 18.9 | 21.0 | 28.0 | 18.5 x $10^6$ tons | 3.7 | 4.0 | 4.4 | 5.9 |
| Iron foundry cupola | 10,000 tons | 15.1 | 16.3 | 18.1 | 24.2 | 13.1 x $10^6$ tons | 19.8 | 21.4 | 23.7 | 31.7 |

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[a] See footnote (b), Table 1, for definition of BICD.

Table 47 summarizes the estimated annual costs of controlling fine particulate emissions via the BICD standard in selected industries, expressed in terms of appropriate production units for each industry. Table 48 presents the unit values of the output from selected industries which were used to develop the data in Table 47.

As is evident from the data in Table 47, the economic impact of fine particulate control will vary substantially from industry to industry. For example, at the 20% capital charge rate (reflecting a 10-year equipment life) applied to BICD-level control of coal-fired electric generating plants, the \$0.00012/kwh cost represents < 1.0% of a typical utility's total cost of service. For municipal incinerators, though, control costs could easily add 8 to 10% to the total waste disposal costs. Control costs for cement plants and asphalt plants will fall gnerally in the 1.5 to 4.0% range, while various metallurgical operations in the ferroalloys industry may require control expenditures ranging anywhere from < 0.5% to > 20% of the value of their products.

Table 47. SUMMARY OF FINE PARTICULATE CONTROL COSTS AT BICD-LEVEL CONTROL
($/Unit of Production)

| Source | Annual Production Rate for Model Plant | Fine Particle Control Efficiency | Capital Charge Rate | | | |
|---|---|---|---|---|---|---|
| | | | 0.15 | 0.17 | 0.20 | 0.30 |
| Coal-fired electric plant | 2.4 x $10^9$ kwh | 98.13 | 0.00010 | 0.00011 | 0.00012 | 0.00017 |
| Municipal incinerator | 80,000 tons | 96.71 | 0.444 | 0.486 | 0.550 | 0.763 |
| Cement plant (rotary kiln) | 3.0 x $10^6$ bbls | 99.17 | 0.042 | 0.045 | 0.049 | 0.065 |
| Asphalt plant (rotary dryers) | 90,000 tons | 99.21 | 0.147 | 0.159 | 0.177 | 0.236 |
| Iron and steel | | | | | | |
| (a) Basic oxygen furnace | 1.0 x $10^6$ tons | 99.70 | 0.211 | 0.230 | 0.259 | 0.355 |
| (b) Electric arc furnace | 100,000 tons | 97.64 | 0.501 | 0.537 | 0.592 | 0.774 |
| (c) Sintering (windbox) | 1.46 x $10^6$ tons | 99.10 | 0.190 | 0.203 | 0.224 | 0.292 |
| Ferroalloy | | | | | | |
| (a) Unhooded open electric furnace | 8,000 tons | 60.00 | 25.688 | 27.563 | 30.375 | 39.750 |
| (b) Hooded open electric furnace | 10,800 tons | 87.80 | 4.759 | 5.107 | 5.630 | 7.370 |
| (c) Closed electric furnace | 13,600 tons | 97.52 | 0.276 | 0.298 | 0.331 | 0.441 |
| Lime plant (rotary kiln) | 87,500 tons | 98.43 | 0.200 | 0.216 | 0.240 | 0.320 |
| Iron foundry cupola | 10,000 tons | 98.46 | 1.512 | 1.613 | 1.814 | 2.418 |
| Primary aluminum (electrolytic cells) | 3,000 tons | 94.85 | 6.52 | 6.99 | 7.71 | 10.08 |
| Primary copper | 76,000 tons | 98.85 | 1.455 | 1.595 | 1.805 | 2.505 |

## Table 48. UNIT VALUE OF OUTPUT FROM SELECTED INDUSTRIES

| Industry or Product | Units | Unit Cost or Value ($) |
|---|---|---|
| Electric energy | Kilowatt-hour | 0.015 |
| Municipal refuse incineration | Ton | 10.00 |
| Cement | Barrel | 4.32 |
| Asphalt | Ton | 23.50 |
| Pig iron | Ton | 78.16 |
| Steel | Ton | 187.26 |
| Lime | Ton | 18.00 |

# SECTION IX
## BENEFIT/COST RELATIONSHIPS FOR FINE PARTICULATE CONTROL

### INTRODUCTION

Particulate emissions from a single point source will generally disperse over a wide area at low concentrations. The specific area over which the dispersion occurs will depend on a variety of meteorological and topographical factors, as will the particulate concentrations experienced at any given point within the area.

The economic effects of airborne particulate matter are a function of the particulate concentration, the area over which the dispersion has occurred, the economic values exposed to various concentrations, and the rate of economic loss associated with the interaction between the pollutants and the economic values.

Five categories of economic loss or economic damage can be attributed to the presence of air pollutants. These include effects on: (1) human health; (2) animals; (3) vegetation; (4) materials; and (5) aesthetics. Considerable research effort has been devoted to identifying the economic effects of air pollution in each of these areas, but very little has been accomplished in quantifying the effects. Because of the lack of reliable quantitative data on effects, only a generalized benefit/cost analysis was conducted during this program. The following sections of this chapter present the methodology utilized for the benefit/cost analysis and the main results of the analysis.

### DETERMINATION OF ECONOMIC DAMAGE ATTRIBUTABLE TO A SPECIFIC SOURCE

The approach used to allocate quantitatively the economic damages attributable to a given emission source is based on the following assumptions:

1. Potential economic damage is related to the quantity of particles discharged into the atmosphere.

2. The damage potential is highest near the emission source, decreasing as the distance from the source increases.

3. The total economic damage will be the integrated effects of pollutant concentrations, interaction coefficients, and exposed economic values throughout the entire dispersion area.

4. This integrated total economic damage will be the same as if it were calculated on the basis of an average pollutant concentration, affecting an average economic value, at an average rate of interaction.

5. The particulate concentrations at which the economic damage will be evaluated are 75 $\mu g/m^3$ and 60 $\mu g/m^3$. The former concentrations correspond to the primary ambient air standard for particulates, while the latter is the secondary ambient air standard.

6. A point source having any specified emission rate (lb/hr) of particulates with an average atmospheric residence time of "t" (hr) will generate a sufficient quantity of particles to produce a particulate concentration of 75 and 60 $\mu g/m^3$ in a given volume of air.

7. Given the volume of air having a particulate concentration of 75 and 60 $\mu g/m^3$, and further given the geometric shape of the volume containing that concentration, the area of influence can be calculated.

8. Lacking specific meteorological data, a hemisphere provides a reasonable representation of the atmospheric diffusion of particulate matter from a stationary point source.

9. The area of influence is defined as the area over which a single emission source could cause and sustain a particulate concentration of 75 and 60 $\mu g/m^3$, assuming uniform dispersion throughout a hemisphere, with the point source located at its center.

10. The economic loss factor, or damage intensity rate, is defined as the total annual economic damage incurred per square mile within the area of influence that would be experienced as a direct result of continuous exposure of all economic values within the area of influence to a sustained particulate concentration of 75 and 60 $\mu g/m^3$.

11. The total economic damage allocable to a point source is the product of the area of influence ($mile^2$) and the damage intensity rate ($\$/mile^2$).

12. The economic benefits resulting from pollution control measures represent the difference between the total economic damage incurred from an uncontrolled emission and the total economic damage incurred from the reduced level of pollutants discharged from the controlled source.

13. Economic values and loss factors are assumed to remain constant throughout the area influenced by a specific pollutant source. However, the area of influence decreases as the quantity of particles discharged decreases, and the total economic losses will decrease in direct proportion to the area of influence.

14. The area of influence varies with the 2/3 power of the quantity of particles discharged. Thus, an order-of-magnitude increase in particulate emissions would increase the area of influence, and also the total economic damage, by $10^{0.667}$, or 4.63 times its previous level. Similarly, a 90% control efficiency on a particulate source would decrease the area of influence and total economic loss to 21.4% of its former level.

It must be recognized that the economic losses computed in this manner are allocated rather than actual; actual losses would be incurred over a much larger area at a much lower rate. However, the total economic damage should be essentially comparable.

## Computing the Impact Area

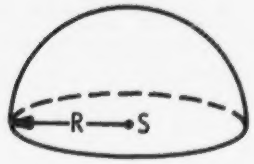
The radius of the hemispheric dispersion model (see Figure 21) is a function of the emission rate and the residence time in the atmosphere of the particles emitted. Equations (6) and (7) present the expressions for the radius of the hemisphere for ambient concentrations of 75 and 60 $\mu g/m^3$, respectively.

$$R = 0.0867\ (Et)^{1/3} \text{ for } 75\ \mu g/m^3 \tag{6}$$

$$R = 0.0954\ (Et)^{1/3} \text{ for } 60\ \mu g/m^3 \tag{7}$$

where R is the radius in miles, E the emission rate in lb/hr, and t the particle residence time in the atmosphere in hours.

The area of influence or impact area for each concentration level is given by Eq. (8) or Eq. (9).



S = Point Source of Pollutant Emissions

R = Radius of Impact Area

$\pi R^2$ = Area of Economic Impact at Critical Concentration

Figure 21. Simplified hemispherical pollutant dispersion model

$$A = 0.0236\ (Et)^{2/3} \text{ for } 75\ \mu g/m^3 \quad (8)$$

$$A = 0.0286\ (Et)^{2/3} \text{ for } 60\ \mu g/m^3 \quad (9)$$

where A is the impact area expressed in square miles.

## Control Costs

Control costs are known to vary inversely with control efficiency. The control cost/control efficiency relationship, furthermore, is believed to be exponential, in that the control cost per unit of control efficiency increases with increasing control efficiency. Thus, the cost of achieving each additional percent of control efficiency costs more than did the last percent improvement, and less than the next.

The general cost efficiency relationship for particulate control systems has this form:

$$C = 0.8(1/U)^{0.3} \quad (10)$$

where C is the annualized cost per CFM of control system capacity for achieving a specified level of control efficiency, with U being the percent of total emissions remaining uncontrolled.

Using this equation, a 90% control efficiency would be expected to cost in the neighborhood of $0.8(1/10)^{0.3}$, or \$0.40/CFM of capacity. Similarly, a 99% control efficiency would cost $0.8\ (1/1)^{0.3}$, or \$0.80/CFM; and increasing the efficiency to 99.9% would raise control costs to $0.8(1/0.1)^{0.3}$, or \$1.60/CFM.

## Economic Damage

The economic damage associated with exposure to a 75 or 60 $\mu g/m^3$ concentration of particulate will depend on the specific characteristics of the area affected, with population density the most important single factor.

The total economic damage to humans, animals, vegetation, materials, and aesthetics attributable to sustained exposure to atmospheric pollutants may range from less than \$10,000/mile$^2$ in sparsely populated rural areas, to more than \$1 million/mile$^2$ in populous urban and industrial locations.

In densely populated urban areas, effects on human health are by far the most important; in sparsely populated rural areas, effects on animal and vegetation are more economically significant; and in moderately populated areas encompassing both urban and rural characteristics, materials and aesthetics are the chief recipients of air pollution damage.

Some effects, then, are related primarily to population density, while others are more dependent on the characteristics of the area exposed to the pollutants. Data are not available, however, to permit accurate quantification of the economic effects of air pollution in any specific category. The estimates presented here are based on a review of the literature, and are intended for illustrative purposes only.

Human Health Damage - The economic effect of a 75 and 60 $\mu g/m^3$ fine particulate concentration on human health is estimated at $20 and $16/person/year. These cost figures take into account premature death and losses incurred as a result of air pollution related diseases such as bronchitis, lung cancer, respiratory ailments, cardiovascular illnesses, and cancer. Particulate pollutants are known to be a major cause of bronchitis, an important contributor to lung cancer and respiratory diseases, and a minor factor in cancer and cardiovascular diseases. The total economic cost of these five diseases is reported to be $13.7 billion annually, of which some 20% might be attributed to air pollutants of all types.[94/] Assuming that $1.0 billion in annual health damage results from ambient particulates, the damage can be estimated at about $5.00-$5.50/year/person/20 $\mu g/m^3$. A 75 $\mu g/m^3$ concentration, therefore, would result in damage of about $20/person/year, while a 60 $\mu g/m^3$ concentration would result in damage of about $16/person/year.

Animal Health Damage - Fine particulates at the concentrations considered here would be expected to cause little economic damage to animals, even in predominantly agricultural areas. Cattle population in rural areas may range from about 200/mile$^2$ when the animals are on pasture, to as many as 60,000/mile$^2$ in confined feedlots. However, cattle on feed are generally kept for no more than 4 months, so air pollutants at the prescribed level would have relatively little impact.

Vegetation Damage - Particulate pollutants, except for specific types (e.g., fluorides), are unlikely to have any significant impact on agricultural crops or other vegetation. In farming areas, the total value of crops exposed to pollutants would seldom exceed $100,000/mile$^2$, and the detrimental effect of particulates on crop yields would be less than 5%. The maximum expected economic loss, then, would be less than $5,000/mile$^2$ in exclusively agricultural areas, and would decline with increasing population as the value of exposed vegetation decreases.

Materials Damage - Particulate damage to materials is almost entirely in the form of soiling, and actual economic losses are incurred only when the frequency (or cost) of cleaning is increased. Since the value of materials exposed to damage (or economic loss) by soiling is closely related to population, the resulting damages would be expected to increase with increasing population density. It is unlikely that actual losses due to soiling at the prescribed fine particulate concentrations of 75 and 60 $\mu g/m^3$ would amount to more than \$10/person/year, and materials damage would more likely be in the neighborhood of \$4/person/year.

Aesthetic Damage - Aesthetic damage is the least quantifiable category of economic losses suffered as a result of air pollutants, but is probably second in importance only to health effects. The main aesthetic effect of particulates in the atmosphere is related to visibility. Defining the economic value of various levels of visibility, though, is a perplexing problem.

There is considerable overlapping between aesthetic and materials damage, especially in the area of soiling, in that soiling of materials does not generally cause physical damage to most materials, but does impair human enjoyment or appreciation of them. It is this aesthetic effect that provides the incentive to clean the dirty materials.

Aesthetic damage is related to both population and area; to both the number of people affected and to the area over which the effects are experienced. On a per capita basis, then, aesthetic damages will decline as population density increases, while in total they will rise with increasing population. For the purposes of this study, aesthetic damages at the prescribed fine particulate concentration were assumed to range from about \$50/person in sparsely populated areas down to around \$8/person in congested urban areas.

## TOTAL ECONOMIC DAMAGES

The preceding discussion presented a methodology for assessing the economic damage attributable to particulate pollutants emitted from a specific source. To apply this procedure to a specific urban, rural, or mixed location with the objective of determining total economic damage from sources in that area and the relative contribution of each source, it is necessary to have data on factors such as (1) number and type of sources in a specific location (i.e., emission inventory), rates of emission from specific sources, and economic values exposed to particulate pollutants. Detailed analyses for specific locations were outside the scope of the current program, and only a generalized analysis of total economic damage as a function of population densities was performed.

Table 49 summarizes the estimated economic damages resulting from fine particulate emissions for areas exposed to a concentration of 75 $\mu g/m^3$ with population densities ranging from 10 to 50,000 persons/$mile^2$. Here, the damages have been grouped into three categories because of the difficulties in distinguishing between several closely related areas. The three categories are: (1) human health; (2) animals and vegetation; and (3) materials and aesthetics.

Total estimated economic damages per square mile resulting from a continuous ambient fine particulate concentration of 75 $\mu g/m^3$ are shown in Table 49 to range from \$5,800/$mile^2$ at a population density of 10 people/$mile^2$, up to \$1,602,000/$mile^2$ at a population density of 50,000. Annual per capita damages incurred over the same range vary from \$580 down to \$32/person

These estimated damages are plotted, both in total and on a per capita basis, in Figure 22. Also shown in Figure 22 are population densities typical of different geographic regions and metropolitan areas, ranging from less than 12 people/$mile^2$ over the State of Arizona, to some 75,000 people/$mile^2$ in the Manhattan Borough of New York City. Average population density in the Continental United States is 50 people/$mile^2$.

A typical suburban community consisting of single-family residences will have around 4,000 to 5,000 people/$mile^2$, while central city areas may run two or three times that density. Completely rural areas often have only 20 to 30 inhabitants/$mile^2$.

About 70 to 75% of the total U.S. population lives in urban areas, with the rest in rural areas. Applying these percentages to typical combination of central city, suburbs, and outlying rural areas gives a composite population density as follows:

40% of population at density of 20,000 people/$mile^2$
+ 35% of population at density of 5,000 people/$mile^2$
+ 25% of population at density of 50 people/$mile^2$

= 100% of population at average density of 196 people/$mile^2$

The economic losses suffered over the U.S. as a result of the particulate pollutants would be in the \$12,000 to \$14,000/$mile^2$ range, averaging about \$70/person annually.

## Table 49. ESTIMATED DAMAGES RESULTING FROM FINE PARTICLE POLLUTION AT AN AMBIENT CONCENTRATION OF 75 μg/m$^3$

| | Annual Economic Damage Attributable to 75 μg/m$^3$ Fine Particulate Concentration (\$/mi$^2$) | | | | |
|---|---|---|---|---|---|
| Population Density/mi$^2$ | Human Health | Animals and Vegetation | Materials and Aesthetics | Total Damage | Annual Per Capita Damage |
| 10 | 200 | 5,000 | 600 | 5,800 | 580 |
| 20 | 400 | 4,600 | 1,120 | 6,120 | 306 |
| 50 | 1,000 | 4,100 | 2,100 | 7,200 | 144 |
| 100 | 2,000 | 3,750 | 3,900 | 9,650 | 97 |
| 200 | 4,000 | 3,450 | 6,800 | 14,250 | 71 |
| 500 | 10,000 | 3,100 | 14,500 | 27,600 | 55 |
| 1,000 | 20,000 | 2,900 | 25,000 | 47,900 | 48 |
| 2,000 | 40,000 | 2,700 | 44,000 | 86,700 | 43 |
| 5,000 | 100,000 | 2,450 | 92,500 | 194,950 | 39 |
| 10,000 | 200,000 | 2,300 | 160,000 | 362,300 | 36 |
| 20,000 | 400,000 | 2,150 | 280,000 | 682,150 | 34 |
| 50,000 | 1,000,000 | 2,000 | 600,000 | 1,602,000 | 32 |

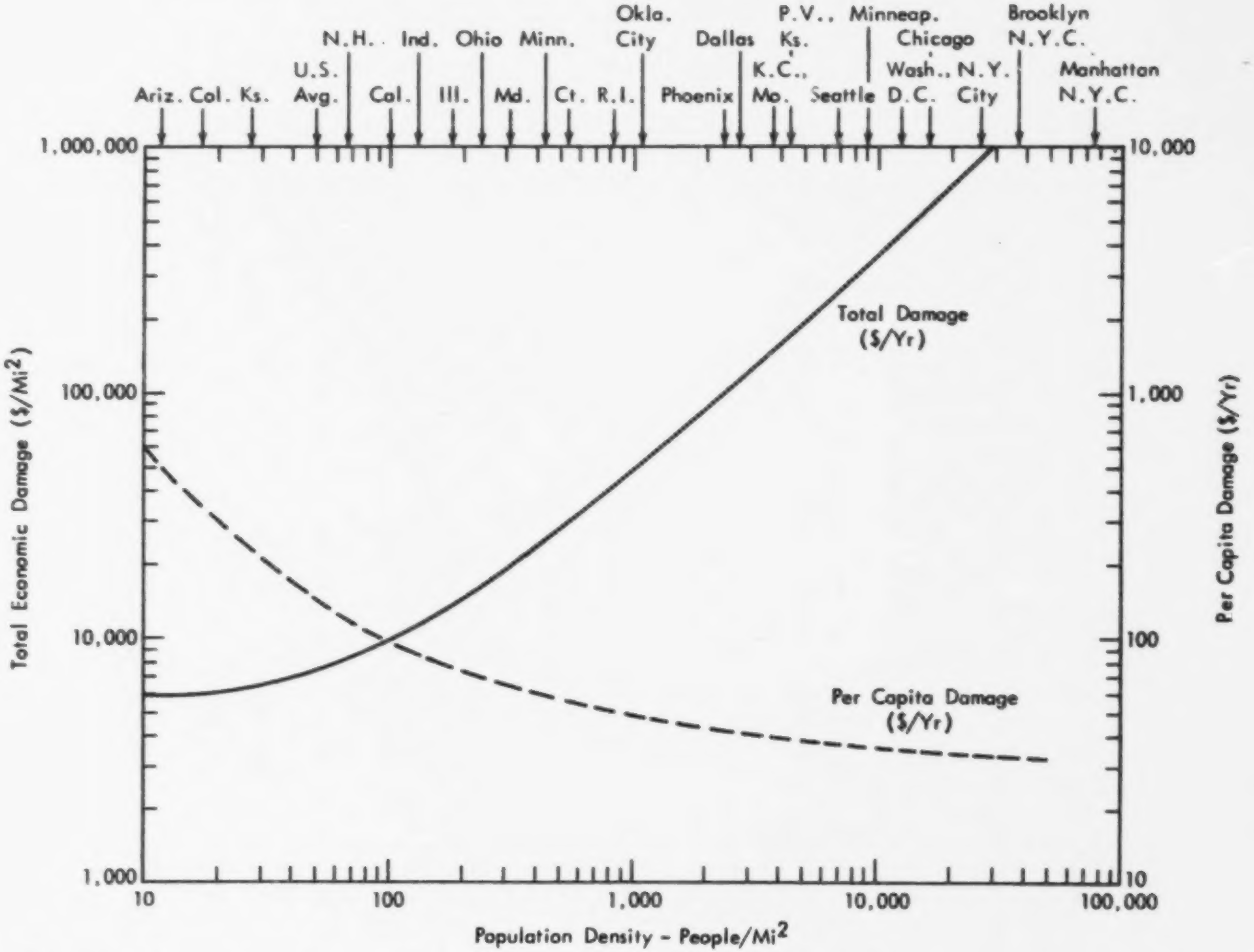


Figure 22. Economic damage resulting from continuous exposure to 75 μg/m$^3$ fine particulate concentration

Table 50 presents a comparison of the estimated damages resulting from fine particle pollution at ambient concentrations of 75 and 60 $\mu g/m^3$. The damage at 60 $\mu g/m^3$ is 80% of the estimated damage at 75 $\mu g/m^3$.

## COST/BENEFIT RELATIONSHIPS

Once the control cost/control efficiency relationships have been established and the economic damage functions defined, a benefit/cost table can be constructed for any given set of conditions. Then, from the benefit/cost table, incremental benefit-cost relationships can be defined. The point at which incremental benefits and incremental costs are equal, or where total economic costs are a minimum, represents the economic optimum control level.

Ultimately, the information thus developed will provide a basis for expressing the optimum control efficiency as a function of the economic damage intensity rate. For example, a control level of 99.7% might be appropriate if the damage potential were \$1.0 million/$mile^2$, while a higher efficiency could be justified in more densely populated areas, and a lower efficiency could be tolerated in areas less susceptible to economic damage.

Calculation of cost/benefit relationships will be illustrated using a coal-fired power plant as an example. Figure 23 illustrates the cost-vs-efficiency relationships for fine particulate control on a 400-MW coal-fired electric generating plant, over the 99.0 to 99.9% control efficiency range. As shown in this figure, total annual control costs (with capital charges included at a 20% annual rate) rise from \$148,000 at 90% efficiency, to an estimated \$580,000 at 99.9% efficiency.

Table 51 shows the extent of impact of the remaining fine particulate emissions from the power plant at various levels of control efficiency, employing the techniques described earlier in this chapter. The economic impact area thus calculated describes the extent over which the prescribed emissions will create and sustain a fine particulate concentration of 75 or 60 $\mu g/m^3$. This area of influence (in $mile^2$) multiplied by the damage incurred per square mile at the specified population density (from Table 49) gives the total damage resulting from the specified emission source.

Tables 52 and 53 bring together the cost of control data from Figure 23 and the damage resulting from the uncontrolled fraction of the fine particulate emissions at populations densities of from 50 to 500 people/$mile^2$, thus developing the total economic cost of fine particulate emissions under the prescribed conditions.

Table 50. COMPARISON OF ESTIMATED DAMAGES RESULTING FROM FINE PARTICLE POLLUTION AT AMBIENT CONCENTRATIONS OF 75 AND 60 $\mu g/m^3$ (\$/mile$^2$)

| Population Density/mi$^2$ | Economic Damage at 75 $\mu g/m^3$ |  | Economic Damage at 60 $\mu g/m^3$ |  |
|---|---|---|---|---|
|  | Total | Per Capita | Total | Per Capita |
| 10 | 5,800 | 580 | 4,640 | 464 |
| 20 | 6,120 | 306 | 4,896 | 245 |
| 50 | 7,200 | 144 | 5,760 | 115 |
| 100 | 9,650 | 97 | 7,720 | 77 |
| 200 | 14,250 | 71 | 11,400 | 57 |
| 500 | 27,600 | 55 | 22,080 | 44 |
| 1,000 | 47,900 | 48 | 38,320 | 38 |
| 2,000 | 86,700 | 43 | 70,080 | 35 |
| 5,000 | 194,950 | 39 | 155,960 | 31 |
| 10,000 | 362,300 | 36 | 289,840 | 29 |
| 20,000 | 682,150 | 34 | 545,720 | 27 |
| 50,000 | 1,602,000 | 32 | 1,281,600 | 26 |

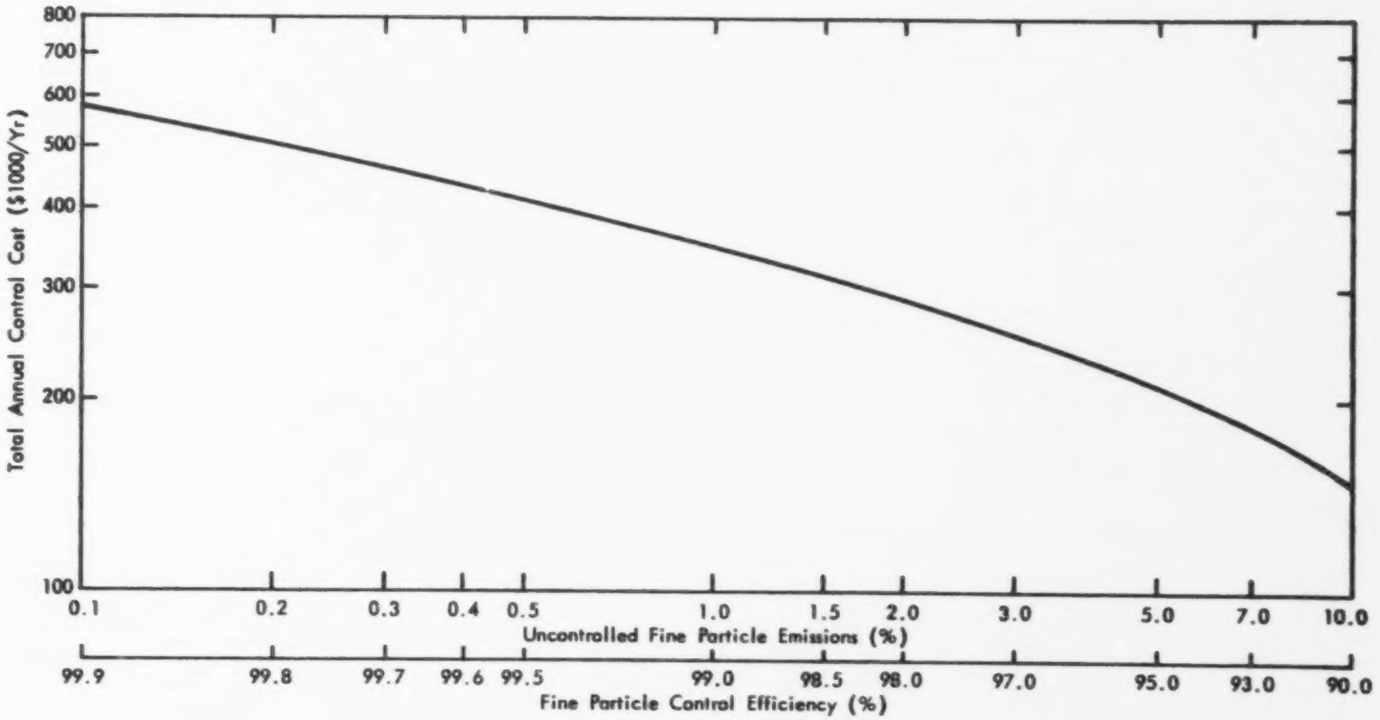


Figure 23. Fine particulate control costs for 400-MW coal-fired electric generating plant

Table 51. EXTENT OF IMPACT OF UNCONTROLLED FINE PARTICLE EMISSIONS FOR 400-MW COAL-FIRED ELECTRIC PLANT

| Fine Particle Control Efficiency (%) | Uncontrolled Fine Particle Emissions (%) | Uncontrolled Emissions (lb/hr) | Fine Particulate Loading at 100 hr Residence Time (lb) | Economic Impact Area at 75 $\mu g/m^3$ ($mi^2$) | Economic Impact Area at 60 $\mu g/m^3$ ($mi^2$) |
|---|---|---|---|---|---|
| 90.0 | 10.0 | 370.0 | 37,000 | 26.30 | 31.76 |
| 91.0 | 9.0 | 330.0 | 33,300 | 24.15 | 29.60 |
| 92.0 | 8.0 | 296.0 | 29,600 | 22.66 | 27.37 |
| 93.0 | 7.0 | 259.0 | 25,900 | 20.73 | 25.04 |
| 94.0 | 6.0 | 222.0 | 22,200 | 18.70 | 22.59 |
| 95.0 | 5.0 | 185.0 | 18,500 | 16.56 | 20.01 |
| 96.0 | 4.0 | 148.0 | 14,800 | 14.27 | 17.24 |
| 97.0 | 3.0 | 111.0 | 11,100 | 11.78 | 14.23 |
| 98.0 | 2.0 | 74.0 | 7,400 | 8.99 | 10.86 |
| 99.0 | 1.0 | 37.0 | 3,700 | 5.66 | 6.84 |
| 99.9 | 0.1 | 3.7 | 370 | 1.22 | 1.47 |

### Table 52. ECONOMIC COSTS OF CONTROL AND DAMAGE CAUSED BY FINE PARTICULATE EMISSIONS AT VARIOUS POPULATION DENSITIES AND CONTROL EFFICIENCIES

| Fine Particle Control Efficiency (%) | Annual Control Cost ($1,000) | Total Annual Cost ($1,000) at Given Population Density for 75 μg/m$^3$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50/mi$^2$ | | 100/mi$^2$ | | 200/mi$^2$ | | 500/mi$^2$ | |
| | | Damage Cost | Total Cost | Damage Cost | Total Cost | Damage Cost | Total Cost | Damage Cost | Total Cost |
| 90.0 | 148 | 189.4 | 337.4 | 253.8 | 401.8 | 374.8 | 522.8 | 725.9 | 873.9 |
| 91.0 | 158 | 173.9 | 331.9 | 233.0 | 319.0 | 344.1 | 502.1 | 666.5 | 824.5 |
| 92.0 | 169 | 163.2 | 332.2 | 218.7 | 387.7 | 322.9 | 491.9 | 625.4 | 794.4 |
| 93.0 | 181 | 149.3 | 330.3 | 200.0 | 381.0 | 295.4 | 476.4 | 572.1 | 753.1 |
| 94.0 | 195 | 134.6 | 329.6 | 180.5 | 375.5 | 266.5 | 461.5 | 516.1 | 711.1 |
| 95.0 | 211 | 119.2 | 330.2 | 159.8 | 370.8 | 236.0 | 447.0 | 457.1 | 668.1 |
| 96.0 | 230 | 102.7 | 332.7 | 137.7 | 367.7 | 203.3 | 433.3 | 393.9 | 623.9 |
| 97.0 | 254 | 84.8 | 338.8 | 113.7 | 367.7 | 167.9 | 421.9 | 325.1 | 579.1 |
| 98.0 | 289 | 64.7 | 353.7 | 86.8 | 375.8 | 128.1 | 417.1 | 248.1 | 537.1 |
| 99.0 | 349 | 40.8 | 389.8 | 54.6 | 403.6 | 80.7 | 429.7 | 156.2 | 505.2 |
| 99.9 | 580 | 8.8 | 588.8 | 11.8 | 591.8 | 17.4 | 597.4 | 33.7 | 613.7 |

Table 53. ECONOMIC COSTS OF CONTROL AND DAMAGE CAUSED BY FINE PARTICULATE EMISSIONS

| Fine Particle Control Efficiency (%) | Annual Control Cost ($1,000) | Total Annual Cost ($1,000) at Given Population Density for 60 μg/m$^3$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50/mi$^2$ | | 100/mi$^2$ | | 200/mi$^2$ | | 500/mi$^2$ | |
| | | Damage Cost | Total Cost | Damage Cost | Total Cost | Damage Cost | Total Cost | Damage Cost | Total Cost |
| 90.0 | 148 | 182.9 | 330.9 | 245.2 | 393.2 | 362.1 | 510.1 | 701.3 | 849.3 |
| 91.0 | 158 | 170.5 | 328.5 | 228.5 | 386.5 | 337.4 | 495.4 | 653.6 | 811.6 |
| 92.0 | 169 | 157.7 | 326.7 | 211.3 | 380.3 | 312.0 | 481.0 | 604.3 | 773.3 |
| 93.0 | 181 | 144.2 | 325.2 | 193.3 | 374.3 | 285.5 | 466.5 | 552.9 | 733.9 |
| 94.0 | 195 | 130.1 | 325.1 | 174.4 | 369.4 | 257.5 | 452.5 | 498.8 | 693.8 |
| 95.0 | 211 | 115.3 | 326.3 | 154.5 | 365.5 | 228.1 | 439.1 | 441.8 | 652.8 |
| 96.0 | 230 | 99.3 | 329.3 | 133.1 | 363.1 | 196.5 | 426.5 | 380.7 | 634.7 |
| 97.0 | 254 | 82.0 | 336.0 | 109.9 | 363.9 | 162.2 | 416.2 | 314.2 | 568.2 |
| 98.0 | 289 | 62.6 | 351.6 | 83.8 | 372.8 | 123.8 | 412.8 | 239.8 | 528.8 |
| 99.0 | 349 | 39.4 | 388.4 | 52.8 | 401.8 | 78.0 | 427.0 | 151.0 | 500.0 |
| 99.9 | 580 | 8.5 | 588.5 | 11.3 | 591.3 | 16.8 | 596.8 | 32.5 | 612.5 |

Here it can be seen that the total economic cost of pollution is, in every case, high when the control level is low (at 90% in the example); costs then decrease as controls increase, until the optimum control level (the point of minimum total cost) is reached; then increase as the benefits of control can no longer justify their costs. These total economic cost-vs-control efficiency relationships are plotted in Figure 24 for the four different population densities.

As would be expected and is clearly evident in Figure 24, a high population density (with its correspondingly high damage cost/mile$^2$) justifies a higher emission control efficiency than does an area populated at low density.

In the example, the optimum control efficiency for a population density of 500/mile$^2$ is 99.1%; for 200/mile$^2$, 97.9%; for 100/mile$^2$, 96.0%; and at 50 people/mile$^2$, 94.0% control is economically justified. These optimum control efficiencies are plotted against population densities in Figure 25.

Using this approach--refined, hopefully, with more reliable cost and benefit data--the optimum control efficiency can be readily determined for any particulate source or combination of sources at any location, employing local characteristics in the analysis. The approach should be equally valid in appraising the economics of control for other air pollutants, providing the relevant data can be developed.

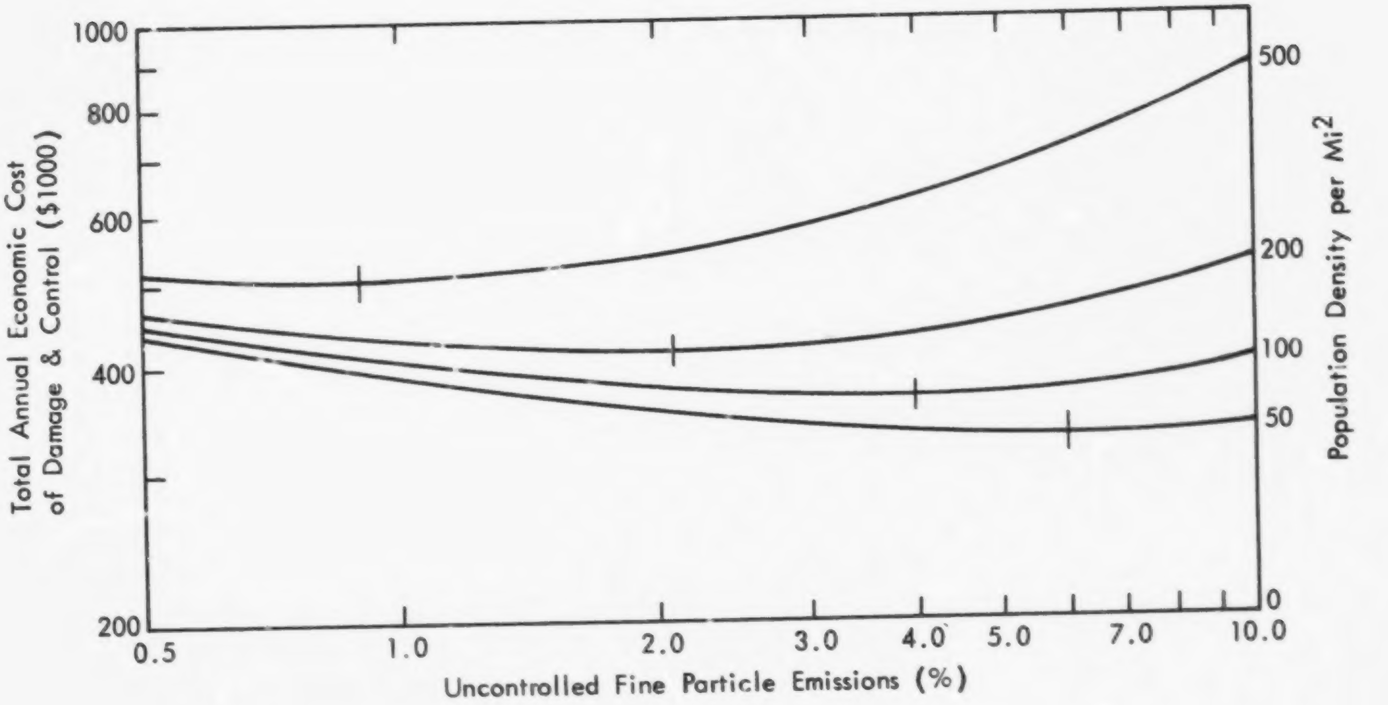


Figure 24. Total annual economic costs of fine particulate control at various population densities

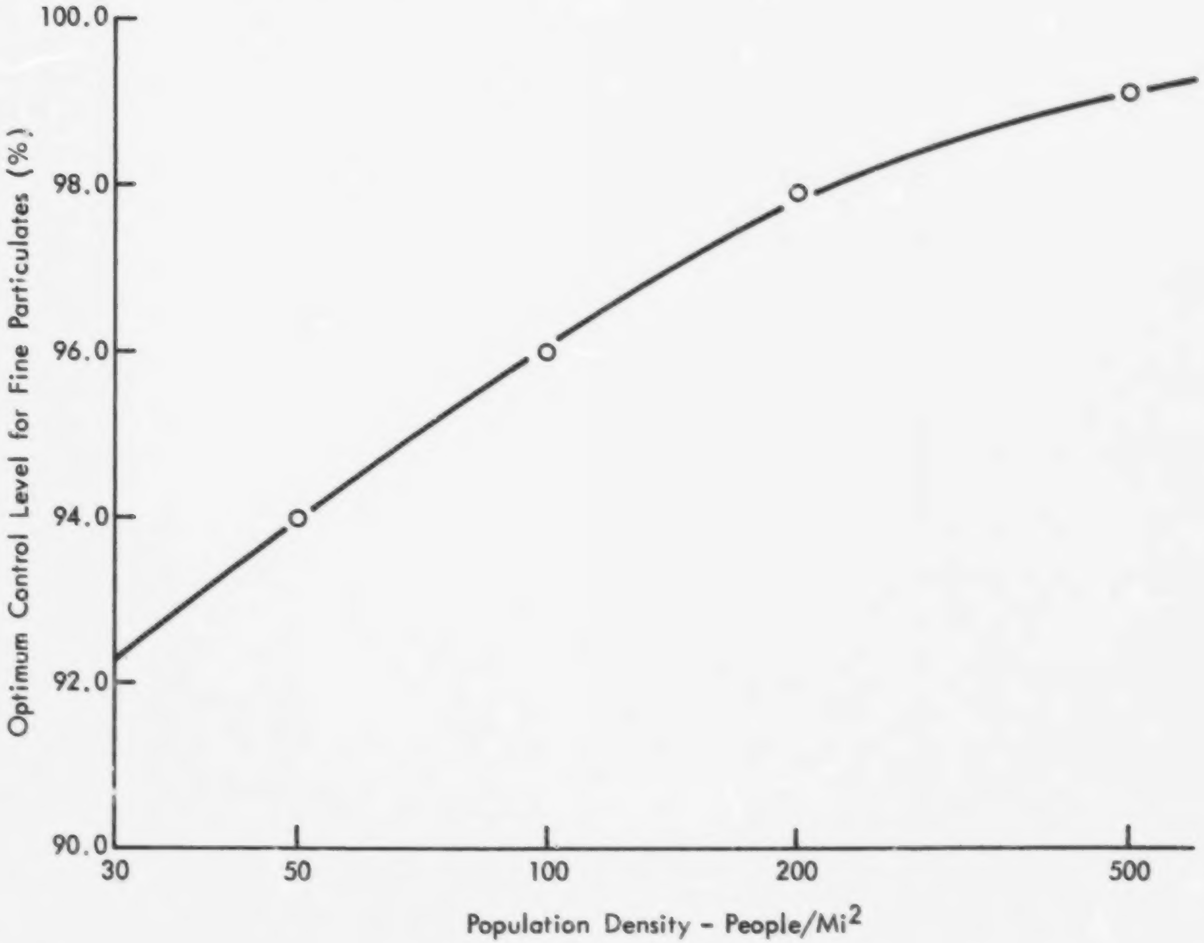


Figure 25. Optimum fine particle control level at various population densities

# SECTION X
## OVERALL FEASIBILITY OF EMISSION STANDARDS BASED ON PARTICLE SIZE

### INTRODUCTION

Our analysis of the implications of emission standards based on particle size has identified some technical deficiencies that will limit the type of standards that can be proposed and implemented in the near future. However, because the technical deficiencies relate primarily to the lack of data on particle size distributions of effluents and control equipment fractional efficiency, there appear to be no insurmountable technical obstacles to emission standards based on particle size.

The economic impact of fine particulate control was found to vary substantially from industry to industry. Estimates of costs associated with the control of fine particulates varied from less than 1.0% up to 20% of the value of the product. The variation in economic impact suggests that it will probably be necessary to consider less restrictive standards for industries that experience a significant adverse economic impact.

The types of emission standards that appear feasible based on existing technical and economic realities are discussed in more detail in the following section.

### FEASIBILITY OF SPECIFIC TYPES OF STANDARDS

Although our analysis of various formats for emission standards, based on particle size was performed in the context of general regulations that might be applied uniformally to all sources, a more realistic approach would be to tailor the emission standard to specific sources of fine particulate pollutants. Tailoring of standards would permit a greater degree of flexibility in an overall control plan for fine particulates, and would acknowledge the differences in the importance and difficulty of control of individual sources.

The exact format of the emission standard(s) that could be proposed and implemented for specific sources will be limited by: (1) collection efficiency in fine particle size range of available control equipment, and (2) availability of source compliance monitoring techniques. Our conclusions regarding the overall feasibility of the various formats for emission standards investigated in this study are presented in the next subsections.

## Opacity Regulations

Regulation of plume opacity provides a viable method of reducing the emission of fine particulates from stationary sources. Opacity standards appear to be the easiest to implement of the alternatives analyzed in the current program. The data base for determining control equipment performance requirements necessary for compliance with opacity standards is more extensive than that available for other alternative emission standards.

Our analysis of the control equipment efficiency required for compliance with a 10% or 5% opacity regulation indicated that for most sources the opacity regulations would not impose collection efficiencies exceeding existing equipment capability. Even with allowance for inadequacies in some of the data used to determine the collection efficiencies needed to attain 10% and 5% plume opacity for specific sources, compliance with stringent opacity regulations would not generally require installation of control equipment that exceeds the efficiency of the best control device currently in use on that source.

Commercial transmissometers are available for measuring the in-stack opacity of particulate emissions. Although additional field testing needs to be conducted to define the performance of transmissometers on several different types of sources, transmissometers provide a suitable, demonstrated technique for instrumental evaluation of the compliance of a source with opacity regulations. With completion of additional field testing, transmissometers should rapidly achieve the status of "off the shelf" technology.

Since the opacity standards would generally require the installation of control equipment that does not exceed the performance capability of the best available technology, the estimated economic impact of opacity standards is less severe than that for other alternatives analyzed in this study. The extent of reduction in the emission of fine particulates is also lowest of the alternatives studied for the same reason.

### Regulation Based on Best Installed Control System

An emission regulation which specifies that a source cannot emit fine particulate in a quantity exceeding that which would be emitted from the same source equipped with the best control device currently being installed on that source is obviously feasible. A regulation of this type merely specifies that all sources must be equipped with the best control system currently in use for the specific source category.

The major unknown regarding the use of the BICD concept as an emission standard is the degree of emissions reduction that can actually be achieved. As noted in Appendix A, only a limited amount of reliable data is available on the fractional efficiency characteristics of control equipment. In order to determine the actual collection efficiency of control equipment in the fine particle size range, extensive field testing will be required with reliable sampling techniques.

A standard requiring installation of the best control system currently in use will have nearly the maximum economic impact on industrial sources. The economic impact analysis presented in Chapter 6 clearly demonstrates this observation. Maximum reduction in fine particle emissions would also be achieved by such an emission standard.

### Mass Emission Regulations

A mass emission standard specifying the maximum amount of particulate less than a given particle size which can be emitted from a source is the most direct approach to regulating the emission of fine particulates. An almost unlimited number of emission standards might be formulated using restriction of mass emissions.

The concept of potential-emission rate offers an interesting basis for emission standards based on particle size. Regulations based on this concept would establish emission limits which vary with the pollution potential of the source, e.g., limitation of the mass rate of fine particle emissions in pound per hour as a function of potential-emission rate of fine particulates, also in pound per hour. Regulations of this type could be tailored to control (1) specific sources of fine particulate pollutants; (2) specific size ranges within the fine particulate range; or (3) specific components of the fine particulate stream emitted by a given source.

In general, mass emission regulations are a feasible vehicle for reducing the emission of fine particulates, and they are the most flexible of all the types of standards considered in this study. Because of the inherent flexibility afforded by the use of mass emission rates as a basis for fine particle emission standards, the extent of reduction in emissions for specific sources can be carefully selected and the technical and economic impact can be tailored to fit the realities of a specific industrial category.

To obtain maximum utilization of a mass emission regulation, it will be necessary to broaden the data base on fine particulate emission rates and control device fractional efficiency.

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# SECTION XII
## GLOSSARY OF TERMS

A = Area

b = Extinction coefficient

c = Annualized cost

$C_c$ = Average efficiency of control equipment

$C_t$ = Percentage of the production capacity on which control equipment has been installed

E = Emission rate, tons/year

$e_f$ = Emission factor (uncontrolled), pounds/ton

g(r) = Mass distribution function

I = Intensity of transmitted light

$I_o$ = Intensity of incident light

$K = \frac{\text{Specific particulate volume}}{\text{Extinction coefficient}}$

L = Visual range

M = Mass concentration

m = Refractive index of the particles relative to air

n(r) = Size frequency distribution, number of particles of radius r per volume per $\Delta r$

P = The production rate, tons/year

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$Q_E(\alpha,m)$ = Particle light extinction efficiency factor, the total light flux scattered and absorbed by a particle divided by the light flux incident on the particle

$r$ = Particle radius

$t$ = Time

$R$ = Radius

$T$ = Plume transmittance

$W$ = Mass concentration of particles in exhaust stream

$\alpha$ = Size parameter, $2\pi r/\lambda$

$\lambda$ = Wavelength of light

$\rho$ = Particle density

# SECTION XIII

# APPENDICES

## CONTROL TECHNOLOGY FOR FINE PARTICLES

### INTRODUCTION

The technology applicable to the control of fine particles is the same as for any particulate emissions, but with interest centered on the higher efficiency equipment. Currently available devices include electrostatic precipitators, wet scrubbers, fabric filters and afterburners. New control devices are under development with the aim of removal of fine particles at lower cost or more efficiently. Characteristics of both the conventional devices and some new devices and control concepts are described in the following sections of this appendix.

### CURRENTLY AVAILABLE CONTROL TECHNOLOGY

The control devices currently available for controlling fine particle emissions are generally the same as those usually considered for controlling total particulate emissions, that is, electrostatic precipitators, fabric filters, scrubbers and afterburners. However, to date there has been little incentive for manufacturers to investigate the ability of their equipment to remove fine particles.

Currently, control equipment is rated mainly by one parameter, namely, overall mass efficiency. Specification of control equipment efficiency by overall performance is inadequate with respect to fine particle emissions. Penetration (i.e., 1-mass efficiency) in specific size ranges is a more revealing term for rating control equipment performance. Correlations of penetration vs particle size are called "fractional efficiency curves." Table A-1 presents typical data on average collection efficiencies for various particle sizes and various particulate control equipment.1/

Midwest Research Institute, under contract from EPA, has been conducting several studies involving the control of fine particulate emissions

Table A-1. AVERAGE COLLECTION EFFICIENCIES FOR VARIOUS PARTICLE SIZES AND VARIOUS PARTICULATE CONTROL EQUIPMENTS[a]

| | Efficiency, %, in Micron Range | | | | | |
|---|---|---|---|---|---|---|
| Type Collector | Overall | 0-5 | 5-10 | 10-20 | 20-44 | > 44 |
| Baffled settling chamber | 58.6 | 7.5 | 22 | 43 | 80 | 90 |
| Simple cyclone | 65.3 | 12 | 33 | 57 | 82 | 91 |
| Long-cone cyclone | 84.2 | 40 | 79 | 92 | 95 | 97 |
| Multiple cyclone (12-in. diameter) | 74.2 | 25 | 54 | 74 | 95 | 98 |
| Multiple cyclone (6-in. diameter) | 93.8 | 63 | 95 | 98 | 99.5 | 100 |
| Irrigated long-cone cyclone | 91.0 | 63 | 93 | 96 | 98.5 | 100 |
| Electrostatic precipitator | 97.0 | 72 | 94.5 | 97 | 99.5 | 100 |
| Irrigated electrostatic precipitator | 99.0 | 97 | 99 | 99.5 | 100 | 100 |
| Spray tower | 94.5 | 90 | 96 | 98 | 100 | 100 |
| Self-induced spray scrubber | 93.6 | 85 | 96 | 98 | 100 | 100 |
| Disintegrator scrubber | 98.5 | 93 | 98 | 99 | 100 | 100 |
| Venturi scrubber | 99.5 | 99 | 99.5 | 100 | 100 | 100 |
| Wet impingement scrubber | 97.9 | 96 | 98.5 | 99 | 100 | 100 |
| Baghouse | 99.7 | 99.5 | 100 | 100 | 100 | 100 |

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[a] Data based on standard silica dust with the following particle distribution:

| Particle Size Range Microns | Percent by Weight |
|---|---|
| 0-5 | 20 |
| 5-10 | 10 |
| 10-20 | 15 |
| 20-44 | 20 |
| > 44 | 35 |

from stationary sources. A part of this effort has involved the evaluation of information that is available on the fractional efficiency measurements of different control devices.[2] Our analysis indicated that a major portion (over 95%) of the data currently available on the particle size of particulates emitted from industrial sources has been obtained by sampling and particle sizing techniques that are not suitable for the particle size range $< 2\ \mu$. As a result, only a meager quantity of accurate data is available on particle size in the $< 2\ \mu$ size range for effluents from uncontrolled or controlled sources. As a result, the ability of control devices to collect the $< 2\ \mu$ particles is ill-defined.

Figures A-1 to A-4 illustrate some of the available fractional efficiency data.[2] Log-probability coordinates were used in order to magnify the efficiency relationship for the smaller particles. All available information relating to specific type of device, overall efficiency, operating conditions (such as pressure drop or water rate, etc.), and sampling and analysis techniques are included. Figure A-1 illustrates data for electrostatic precipitators, while Figure A-2 presents fabric filter fractional efficiency. Wet scrubber characteristics are given in Figures A-3 and A-4. The data for each type of device varied over a wide range, but this variation is not surprising considering the variations in types and design of devices, testing procedures, operating conditions and particle size analysis techniques.

Since the data for each type of device did vary over a wide range, the curves were examined with the objective of drawing general curves that would represent low, medium, and high overall efficiencies for each type of device. The data for each type of control device were carefully assessed to determine the general fractional efficiency curves shown in Figure A-5.[2]

## Performance Capabilities of Current Equipment

The fractional efficiency curves described in the preceding section show that even though the control devices can achieve overall mass efficiencies in excess of 99%, their ability to remove fine particles is often significantly less.

Variations in the usual control equipment designs may increase the capabilities of these devices. One such variation is the wet electrostatic precipitator in which water removes the collected material and often makes possible the use of electrostatic precipitation on sources where it would otherwise not be suitable. Preconditioning of effluent and injection of $NH_3$ or other gases has also been used to change the resistivity of the dust to permit better collection in electrostatic precipitators.

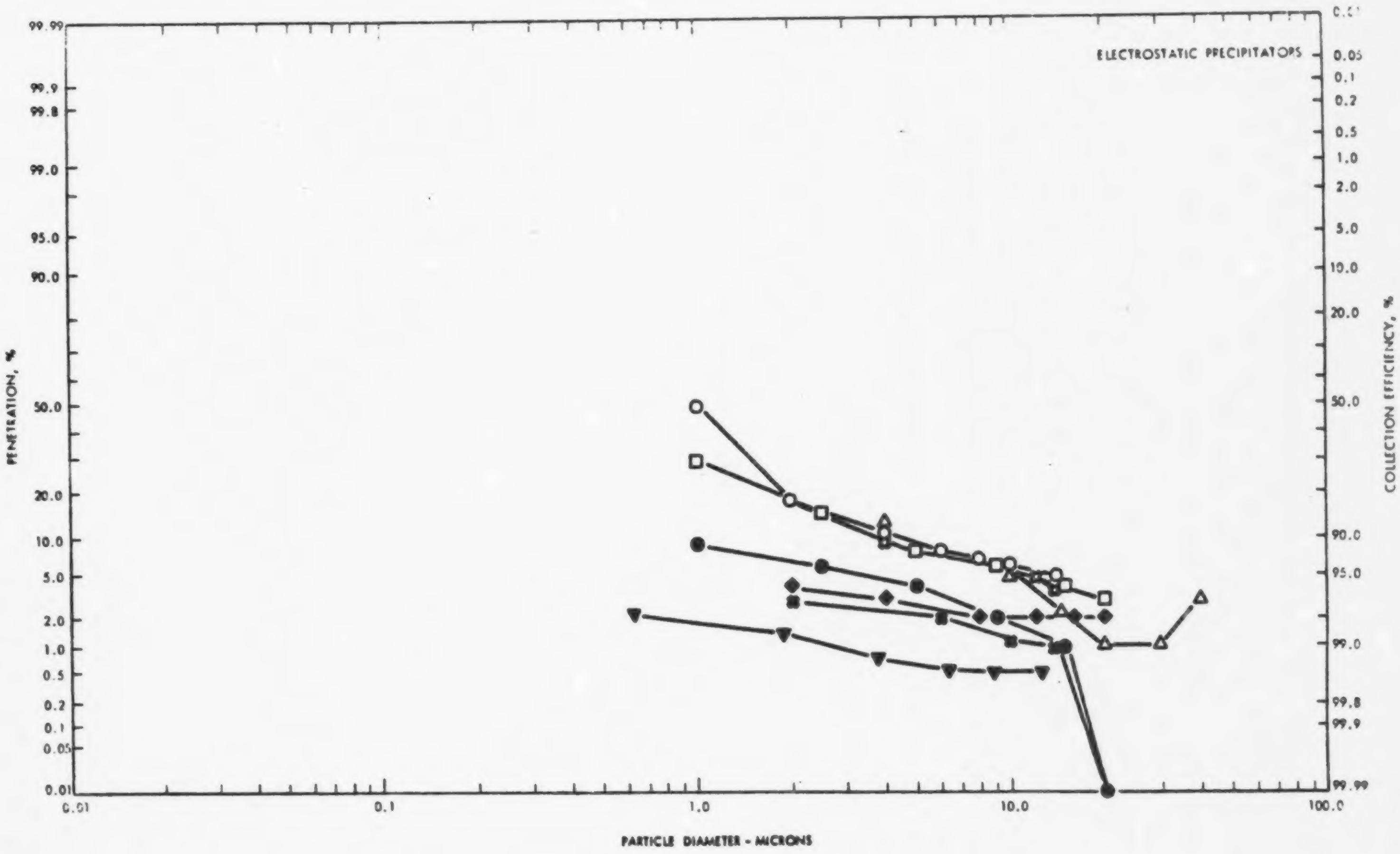

Figure A-1. Fractional efficiency data for electrostatic precipitators

## Symbol Identification for Figure A-1

□ Stairmand, Dry ESP

● Stairmand, Irrigated ESP

◆ Well Conditioned Dust, Particle Sizing by Electron Microscope

✚ Wet ESP, High Resistivity Dust, Particle Sizing by Electron Microscope

○ No Information Except 99.9 % Efficient

✙ No Information Except 99.9 % Efficient

▼ Pilot Scale ESP on Coal-Fired Boiler; Gas Velocity 2.62 Ft/Sec

△ "Typical" Curve

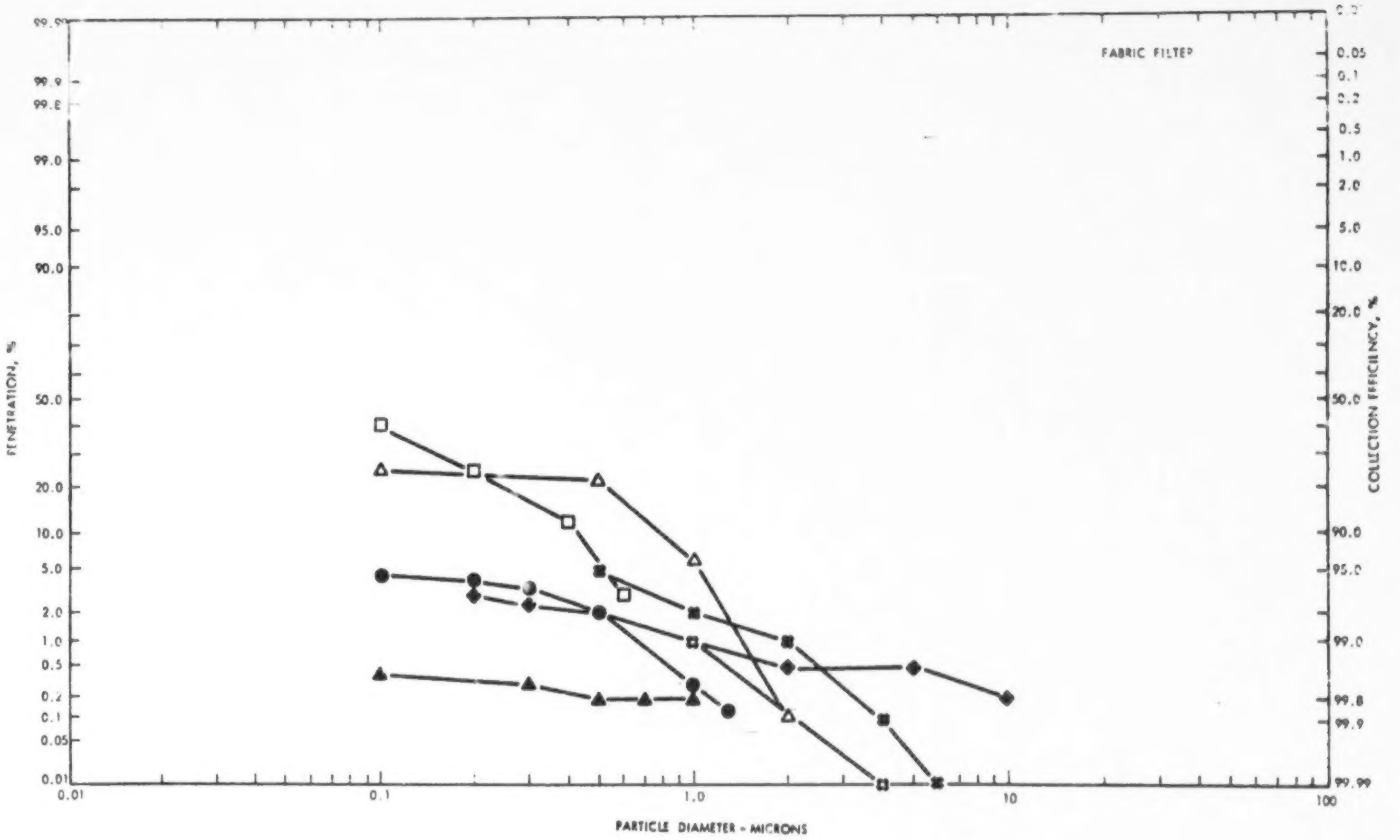

Figure A-2. Fractional efficiency data for fabric filters

Symbol Identification for Figure A-2

△ 35 Shakes, Precoated, Monodisperse Aerosol, 1-4 In. $\Delta$

▲ Loaded, Precoated, Monodisperse Aerosol, 1-4 In. $\Delta P$

✖ No Information Except 99.9 + % Efficient

✕ No Information Except 99.9 + % Efficient

● Data Using Cascade Impactor, Shake Type Collector, Very Low $\Delta P$

◇ Data Using Cascade Impactor, Ultrajet Type Collector, 10-12 In. $\Delta P$

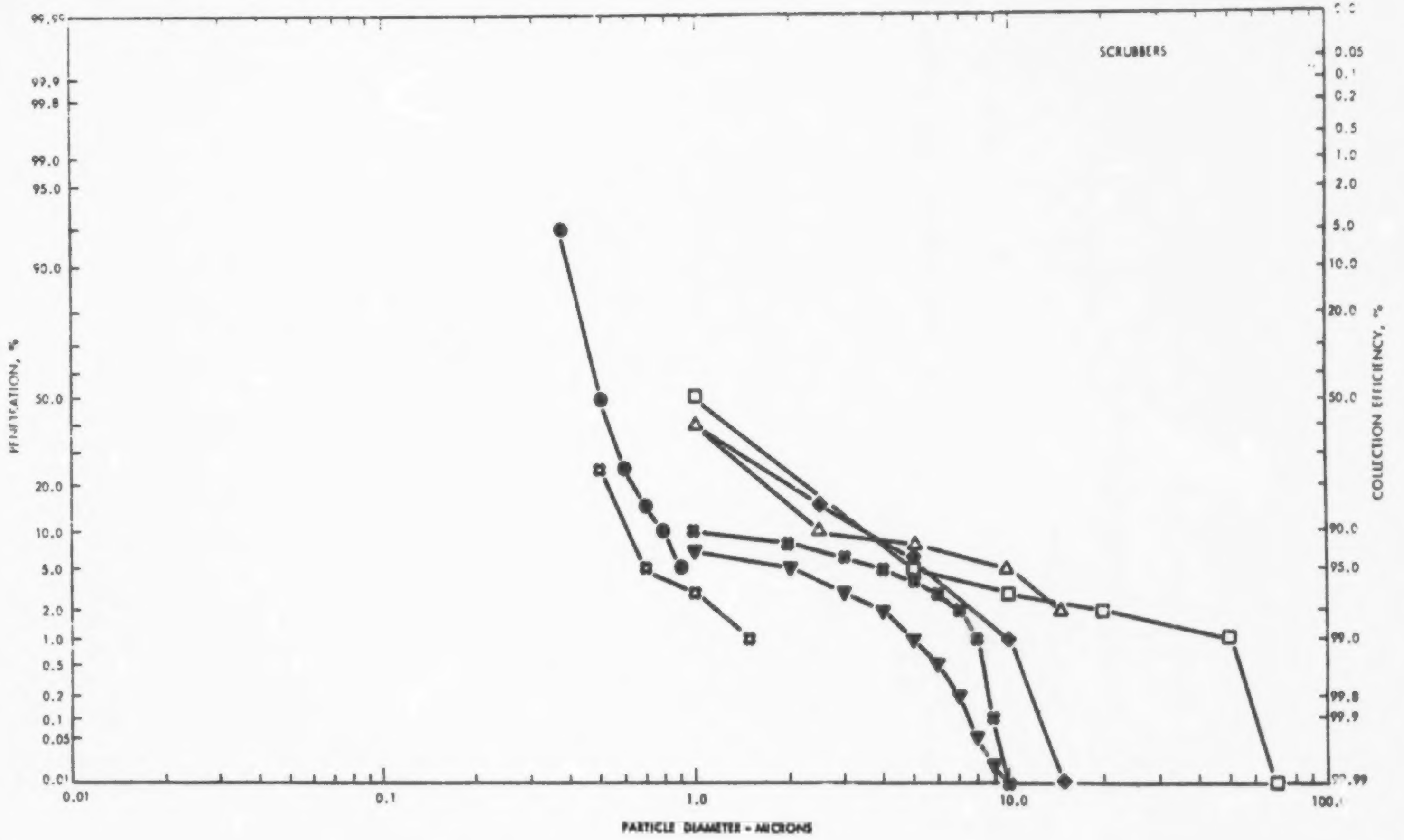

Figure A-3. Fractional efficiency data for wet scrubbers

## Symbol Identification for Figure A-3

| | |
|---|---|
| △ | Stairmand, Gravity Spray Tower, Less Than 1 In. $\Delta P$ |
| ✖ | Stairmand, Impingement Scrubber |
| ◆ | Stairmand, Orifice Scrubber |
| ▼ | Stairmand, Venturi Scrubber |
| ● | Spray Tower, Soluble Dust $(Na_2, SO_4)$, Optical Counter, Liquid Flowrates Approximately 0.03 Ft$^3$/Min |
| ☐ | Venturi Scrubber "Typical" Curve |
| ✙ | Venturi Scrubber, $H_3PO_4$ Plant Mist, Approximately 30 In. $\Delta P$ |

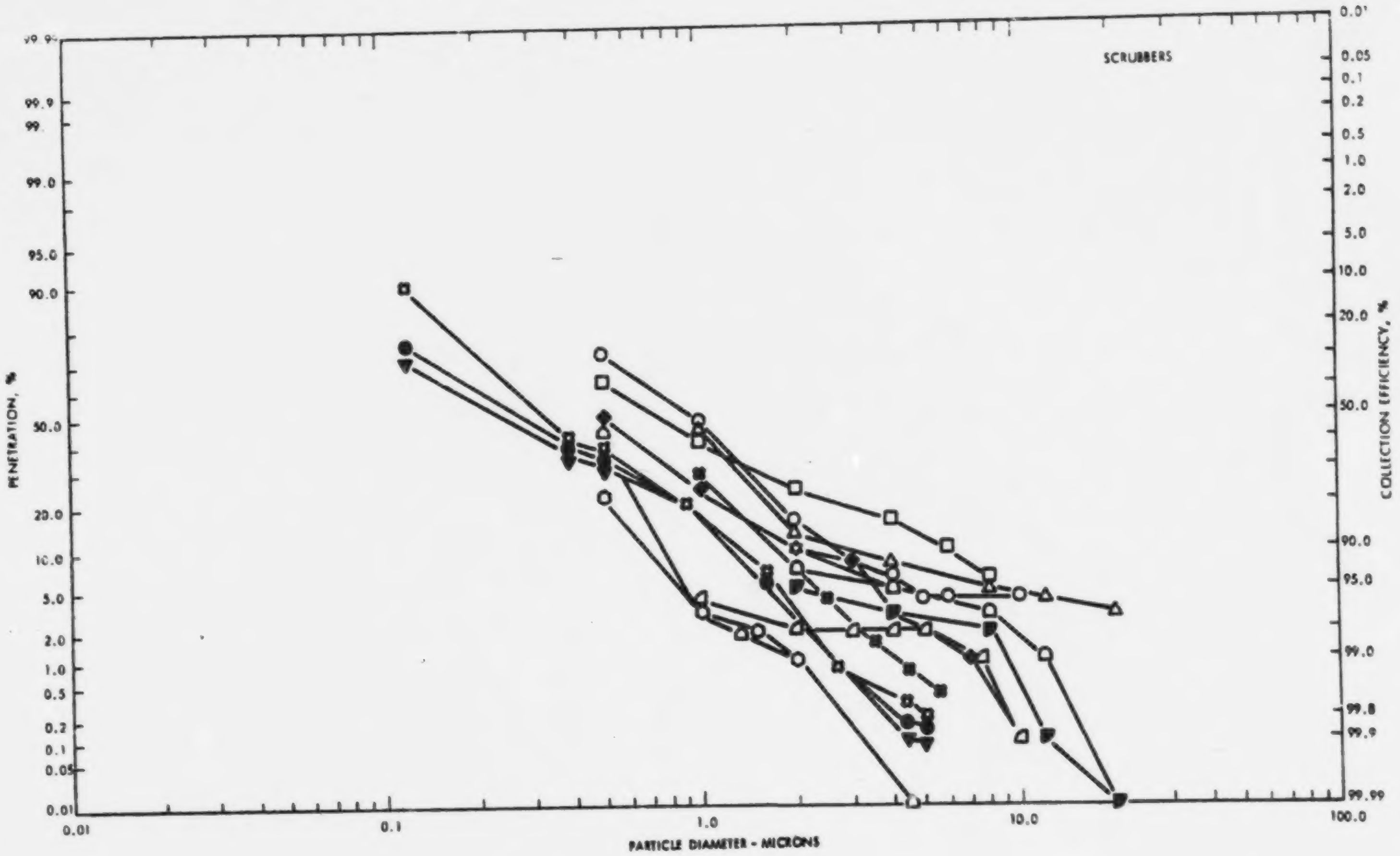

Figure A-4. Fractional efficiency data for wet scrubbers

## Symbol Identification for Figure A-4

□ Data Using Cascade Impactor

◗ 4-6 In. $H_2O$ $\Delta P$, 4 gpm/1,000 cfm

⌂ 4-6 In. $H_2O$ $\Delta P$, 3.3 gpm/1,000 cfm

✡ 4-6 In. $H_2O$ $\Delta P$, 3.0 gpm/1,000 cfm

✿ Perforated Plate Scrubber, 3 Plates, 2,750 cfm, Vane Separator, Water Recycled, 12 In. $\Delta P$

● Perforated Plate Scrubber, 3 Plates, 2,750 cfm, Venturi Separator, Water Recycled, 12 In. $\Delta P$

▼ Perforated Plate Scrubber, 3 Plates, 2,750 cfm, Venturi Separator, Fresh Water, 12 In. $\Delta P$

✱ Asphalt Plant, Wet Scrubber, Low $\Delta P$

◿ Venturi Scrubber (1967), Throat Velocity 17,800 Ft/Min

◆ Orifice Scrubber (1967), 6 In. $\Delta P$

○ Wet Centrifugal Scrubber (1967), 3.5 In. $\Delta P$

⬡ Venturi Scrubber, 30 In. $\Delta P$, $H_3PO_4$ Mist

△ Stairmand, Spray Tower, 1 In. $\Delta P$, 18 Gal/1,000 cf

⌂ Stairmand, Venturi Scrubber, 6 In. Throat, 3,500 cfm Gas

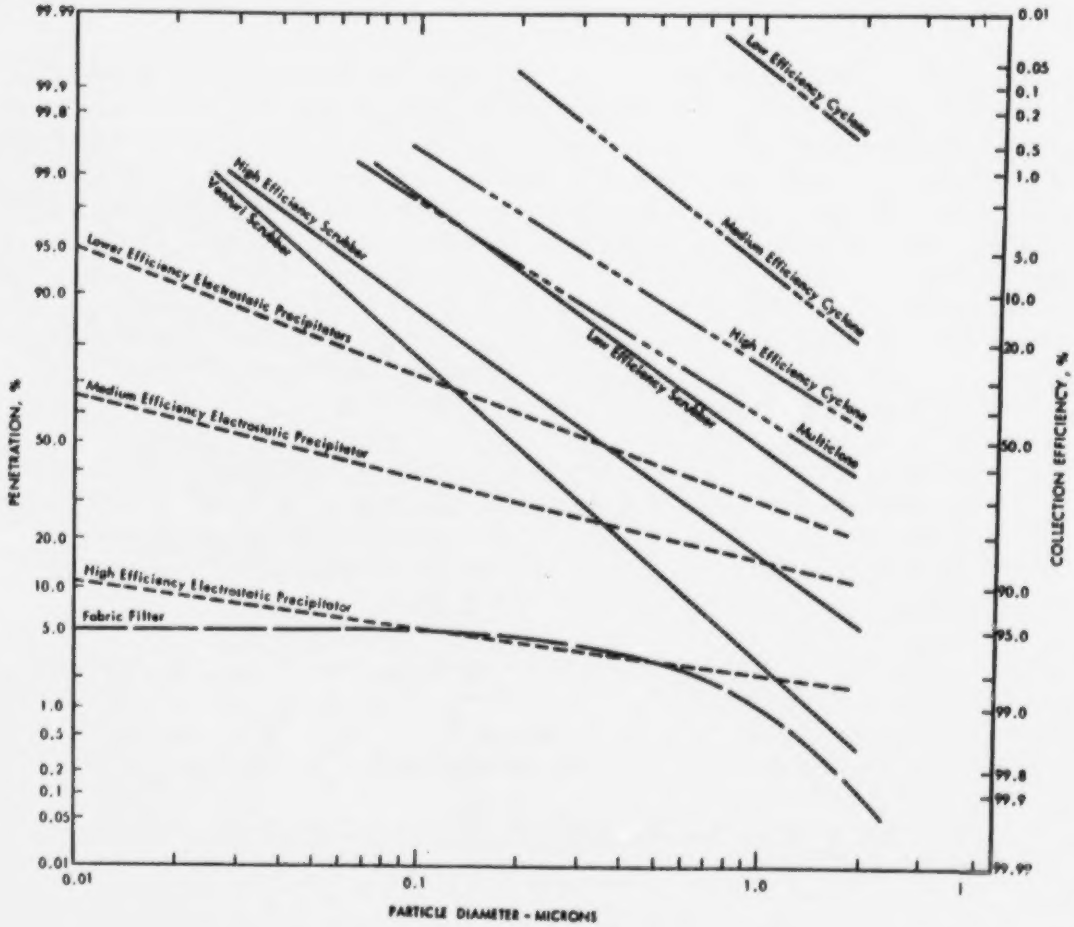

Figure A-5. Extrapolated fractional efficiency of control devices

One of the largest users of electrostatic precipitators has been the coal-fired power plants. Electrostatic precipitators in this service process very large volumes of flue gases at temperatures usually in the range of 300-600°F. Design efficiencies may be as high as 99.7% but the particle size of the flyash emissions is comparatively large.

Wet scrubbers are in wide use in many types of sources and there have been a multitude of variations in design. These devices have generally not been used for controlling sources containing a large percentage of fine particles except for higher pressure drop Venturi scrubbers. Venturi scrubbers are capable of high overall mass efficiencies (> 99%) even on sources containing a higher percent of fumes such as basic oxygen furnaces in the steel industry. More recently, variation in scrubber design for pressure drops on the order of 4-10 in. of $H_2O$ have shown high efficiencies. Examples of this are the marble bed scrubber and the turbulent contact absorber. These types of scrubbers have undergone increased development in connection with $SO_2$ removal processes for power plants, etc.

Fabric filters are usually considered as the highest efficiency device and have been demonstrated to have efficiencies in excess of 99.9%. Variations in design of fabric filters include fabric material and cleaning method. The cleaning method may also permit variations in air to cloth ratio which range from as low as 2 $cfm/ft^2$ up to 25 $cfm/ft^2$.

For many sources, as the applied control device efficiencies are increased, the emissions during periods when the control devices are out of operation or when their operation is impaired become quite significant. Reliability and maintenance requirements are briefly reviewed in the next section.

## Maintenance and Reliability Requirements of Current Equipment with Regard to Control of Fine Particles

Increasingly stringent emission regulations will make it imperative that control devices installed operate reliably. As a first requirement, the control device and all associated equipment must be properly designed with the proper materials of construction and adequate instrumentation to shut the system down or bypass the control device in case of upsets. This is necessary to protect the control equipment; and prevent long and costly downtimes for repairs.

Assuming that the equipment has been properly designed and proper materials of construction used, regular maintenance and inspection schedules must be followed in order to avoid unscheduled downtime for repairs and to prevent deterioration in the operating efficiency of the system. Because the fine particle fraction of any effluent stream is the most difficult to collect, it is this portion of the effluent which will most likely escape collection if the equipment is not kept at its peak operating efficiency.

Each type of control device has its own characteristic problem areas that most frequently occur, leading to decreased efficiency and lowering reliability, if regular maintenance is not practiced. In the case of electrostatic precipitators the most frequently reported problem is breakage of electrode wires which takes that associated section of the precipitator out of operation. This may cause only a small decrease in efficiency but the problem usually cannot be repaired without shutting down all or a large part of the precipitator. References 3 and 4 report the results on a study of the reliability of electrostatic precipitators of various design types serving 51 power generating units of TVA. Figure A-6 indicates the items that contributed to the average unavailability of nine classes of electrostatic precipitators on the TVA system over a recent year's operation.[4/] Reference 3 reported that the overall weighted average availability was 92.6% for a 1-year period of operation.

Wet scrubbers are especially susceptible to corrosion and buildup problems. Corrosion problems are best controlled by choice of construction materials and inspection and repair during regular shutdowns. Buildups of particulate matter or other solids from the scrubbing solution are a problem that may be more difficult to control than corrosion. Both problems of corrosion and buildup will result in decreased efficiency of particulate removal, with the finer particles being the ones most likely to escape collection.

Operational reliability of fabric fibers is related to prevention of overheating or condensation. Any malfunction that causes either situation can quickly ruin the entire set of bags in a fabric filter unit. This not only requires costly replacement of the fabric but also takes the control device out of service until new fabric can be obtained and installed.

Another problem, one that may be difficult to detect, is small holes in the bags. This can occur because of abrasive particulate matter, but it is also often due to improper installation and tensioning of the bags. This latter problem is preventable if regular and proper maintenance inspection and repairs are carried out.

Few people would question the merits of a good maintenance program, but the press of plant operations often cause such programs to be passed over. It is often the nonproduction equipment, such as pollution control devices, that are neglected. Increasingly stringent regulations and monitoring efforts along with required incident reports and penalties are being implemented.

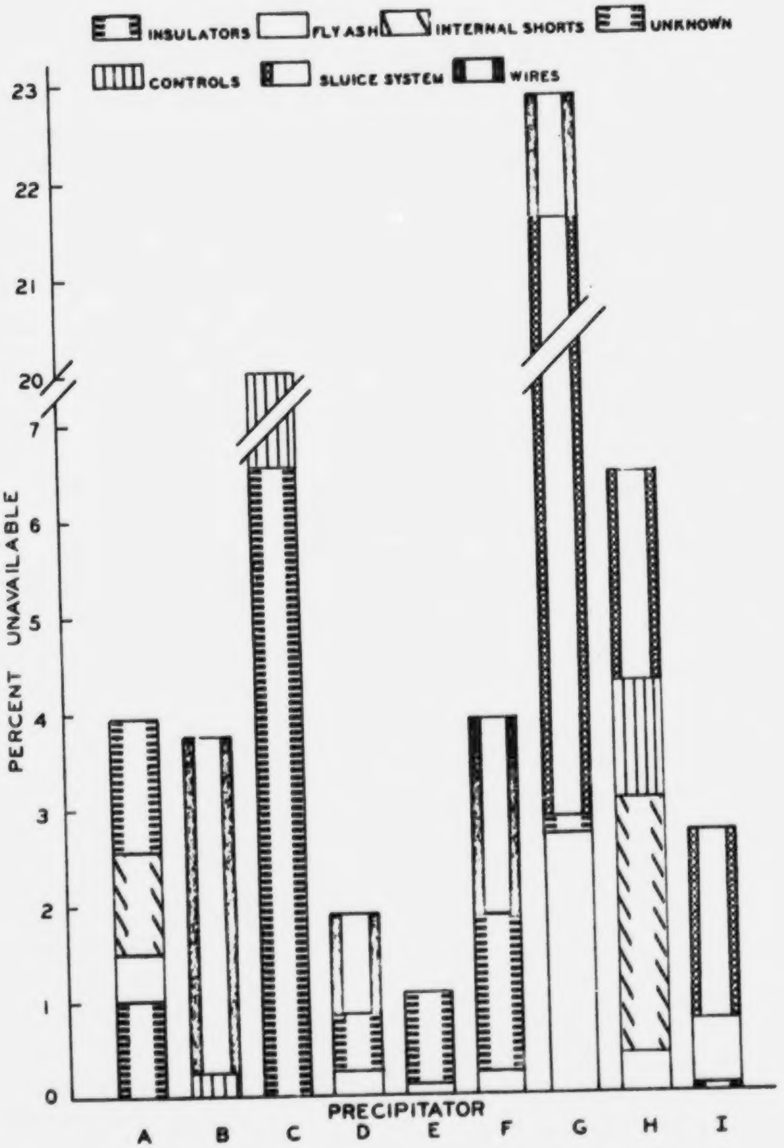

Figure A-6. Electrostatic precipitator unavailability

The incident reports and penalties should help to promote regular maintenance programs to keep the installed equipment operating at its peak with resultant improvement in collection--especially of the fine particle fractions.

## NEW OR EMERGING CONTROL TECHNOLOGY

There are several possible avenues that might lead to improved control of fine particulates. The more promising approaches can be grouped into three broad categories: (1) development of new or novel particulate control devices; (2) augmentation of commonly used collection mechanisms by additional forces that do not approach zero in the $\leq 2\ \mu$ size range; and (3) particle agglomeration techniques.

Recent developments in each area are briefly summarized in the following sections.

### New Control Devices

A variety of devices which are claimed to have high collection efficiencies in the fine particle range have been reported in the literature. Table A-2 presents a list of many of the devices recently reported in the literature. For most of these devices supporting data for the claims of high efficiency are meager, unavailable, or inconclusive. Extensive testing programs will be required to determine the full potential of these devices.

One of the more promising new control devices is the ADTEC system. The ADTEC system is a wet scrubbing system that operates on the conventional Venturi collection mechanism of inertial impaction, but establishes the requisite particle-droplet differential velocity by utilizing waste process heat rather than external energy. On the basis of currently available information, this system appears to offer significant improvement in the collection of fine particles, at modest energy consumption rates, where a waste gas is available which contains a sufficient amount of thermal energy.[6,7]

Control devices utilizing steam condensation also appear to offer promise for improved collection of fine particulates. Condensation phenomena are already utilized in many types of wet scrubbers in that the effluent gas is contacted with water spray resulting in cooling and saturation of the gas stream. However, the efficiency of these devices for removing fine particles is not especially high unless considerable mechanical energy is dissipated during the condensation, such as that which occurs in a Venturi scrubber.

## Table A-2. NEW CONTROL DEVICES FOR PARTICULATE POLLUTANTS

| Control Devices | Manufacturer(s) or Investigator(s) |
|---|---|
| ADTEC wet scrubber | Aronetics, Inc.<br>Tullahoma, Tennessee |
| Aerodynamic immaculator (wet scrubber) | Lone Star Steel Company<br>Lone Star, Texas |
| PENTAPURE$^{TM}$ IMPINGER | Purity Corporation<br>Elk Grove Village, Illinois |
| Nucleation scrubber | Teller Environmental Systems, Inc.<br>New York, New York |
| Condensation Scrubber | Oak Ridge National Laboratory, APT, Inc.<br>University of Melbourne |
| Granular bed filters | Rex-Chainbelt, Inc., Ducon Company<br>Carnegie-Mellon University, City University of New York |
| Fluid beds | University of Idaho,<br>Oregon State University |
| Charged droplet scrubber | TRW, Inc.<br>University of Washington, MIT |
| Space charge precipitator | University of California |
| Pulsed precipitator | Belco Pollution Control |
| Electret filters | Battelle Northwest |

The experimental work of Schauer[8] has demonstrated that condensation accomplished by the use of a diverging nozzle system can produce very high removal efficiency, but this requires excessive quantities of steam. Lancasters' work[9] indicates that condensation phenomena offer a potential means of improving the operational efficiency of existing wet scrubber units but the technique of direct steam injection is inefficient and could only be considered in situations where low pressure waste steam was available.

The inefficient usage of steam appears to be due primarily to inadequate distribution of the steam between potential condensation nuclei. If the efficiency of steam usage can be increased by the design of special condensation scrubbers which adequately distribute the condensed steam among aerosol particles, the system could be competitive with conventional scrubbers in normal applications. For the removal of ultrafine particles, the condensation scrubber may prove to be superior.

### Augmentation of Collecting Mechanisms

Theoretically, improvements in the control of fine particles might result from better exploitation of particle collection mechanisms (e.g., diffusiophonesis, thermophoresis). Such phenomena might be used advantageously for collection of fine particles if devices can be designed to utilize them without unreasonable high energy requirements.

A brief presentation of some of the theoretical aspects and experimental results for these mechanisms is given in the succeeding sections. A more in-depth analysis of these mechanisms, with emphasis on wet scrubber technology, has been carried out by Calvert, et al.[10-12] among others. Equations presented and developed by Calvert plus the many important references, will be of interest to those who may want to continue investigations in this area.

Thermophoretic Forces - Exploitation of thermal forces to improve the collection of fine particles might be accomplished in one of two ways: (1) design and construction of cleaners based entirely on particle deposition by thermal forces; and (2) use of thermal forces as a contributing mechanism in existing dust collectors.

From the standpoint of the collection efficiency of fine particulates, thermal precipitators appear quite promising. However, consideration of the energy requirements presents a different picture. The power required for thermal precipitation would be at least an order of magnitude greater than that required for most other air cleaners. If waste thermal energy is available from the gas stream that is being cleaned, then a thermal precipitator is more attractive from an external energy consumption standpoint.

The deposition of particles from a hot gas in a cooled, packed bed is an instance in which thermal forces may improve collection efficiency. Experiments have shown that when a packed bed is initially cold, particle collection is more nearly complete. Theoretical calculations indicate that, since the passages in a bed are narrow, a temperature difference of 50°C might give rise to a temperature gradient of 1000°C/cm in the passages. Calculations show that this could result in the deposition of 98.8% of the 0.1 μ particles in a 9-in. deep bed.[13/]

Diffusiophoretic Forces - Diffusiophoresis might be a useful mechanism to exploit in conjunction with other mechanisms for the removal of small particulates from gas streams. Diffusiophoresis has the following advantages:

1. The fundamental mechanisms is independent of particle size and becomes more important compared to other removal mechanisms for particles below 2 μ.

2. The particulate removal efficiency that can be expected depends on operating conditions and equipment design but can theoretically reach 100%. In a more practical situation, theory indicates that diffusiophoresis might account for more than 30% of the total collection efficiency.

To exploit the mechanism of diffusiophoresis, the collecting device must be designed such that one component in the gas phase is diffusing toward a collecting surface. The most practical case would be the diffusion of water vapor toward a surface.

## Agglomeration of Particles

The agglomeration or coagulation of particulates could be used as a step in a sequence of operations aimed at controlling the emission of fine particles. If sufficiently large particles can be produced, it may be possible to use conventional low-cost techniques as the final collection step. The movement of particles toward one another may be brought about solely by Brownian motion, but usually other influences play a major role, e.g., turbulence of the fluid, gravitational forces, electrostatic forces, and sonic forces.

The following sections discuss the nature of particle agglomeration with and without the use of external forces, and indicate possible avenues that might be utilized to enhance the control of fine particles.

Agglomeration in Absence of External Forces - When the movement of particles, leading to contact and agglomeration, can be accomplished only by Brownian movement (diffusion), the process is called thermal coagulation.

The major disadvantage of thermal agglomeration is the long time required to grow particles. The only variables which can be used to control particle-particle collision rate are temperature, gas composition and the particle concentration. The temperature and suspending gas composition do not appear to be useful variables.

The possibility of influencing the coagulation rate of particles suspended in air by introducing a second gas or vapor has been explored in several experimental programs, and the only clear-cut results seem to be those in which the added vapor in some way affects the shape of the particles, or in which vapor is actually being transferred between the vapor phase and the particles so that appreciable gaseous diffusion occurs (i.e., diffusiophoresis).

One could conceivably change the particle distribution and concentration by seeding the particle suspension with large particulates to act as "agglomeration sites," but this does not appear very useful based on experimental studies. Thus, thermal agglomeration is not a viable approach to augmenting the ability of control systems to control fine particulate emissions.

Turbulent Agglomeration - Turbulence increases the relative velocities among particulates which in turn increases the chance of particulate collision. Theoretical studies on the coagulation of aerosols in turbulent flow have been conducted by Levich,[13] East and Marshall,[14] Tunitskii,[15] Obukhov and Yaglon,[16] and Beal.[17]

Experimental study of the rate of agglomeration in the presence of turbulence is difficult because turbulence also accelerates the deposition of particles on walls. The rate of deposition increases with particle size so that the assessment of the course of agglomeration from the increase in mean particle size in complicated. Experiments by Yoder and Silverman are the only results that are subject to any rigorous analysis.[18] These investigators performed experiments to obtain data on the deposition and agglomeration of particles in turbulent air flow. In their experimental design, deposition and agglomeration were occurring simultaneously, and their basic problem was to separate the two effects. They did this by measuring both the total number concentration and the fraction of particles which had agglomerated at the inlet and outlet of their test section. By applying theoretical concepts, they could then infer the separate effects of both deposition and agglomeration from the measured parameters. They did not, however, make any direct observation of either phenomenon.

Figures A-7, A-8, and A-9 present some of the results of Beal's theoretical calculations. As shown in Figure A-7, the "exact" solution of the diffusion equation is asymptotic to the solutions based on either Brownian motion or turbulent diffusion alone and does not differ very much from a simple sum of these solutions. Figure A-8 presents the normalized coagulation constant, $K = \frac{N}{n_o}$ , as a function of particle diameter, while Figure A-9 illustrates the variation of the agglomeration rate constant ($Kn_o$) as a function of particle size for a constant mass concentration of $10^{-8}$ g/cm$^3$.

Beal's analysis has several limitations. Only the steady-state solution of the diffusion equation was obtained, only interactions among particles of equal size were considered, and all particles were assumed to stick together on impact. The last assumption is the most tenuous.

Figures A-7 and A-8 indicate that turbulence does not significantly enhance agglomeration for particles less than 0.2 μ in diameter, but can increase the coagulation constant of 0.5 μ particles by about a factor of 10 and 1 μ particles by a factor of $10^2$. The energy expended to accomplish this increase is about $2.7 \times 10^7$ dyne-cm-sec$^{-1}$ or 0.004 hp/g.

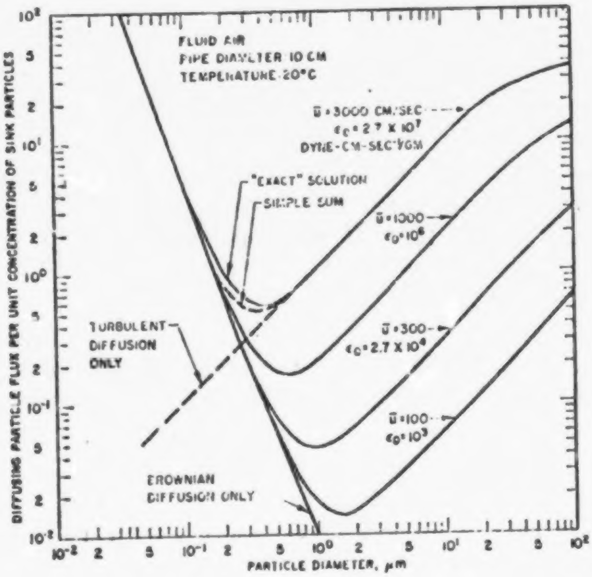

Figure A-7. Particle agglomeration flux for various particle diameters and fluid velocities

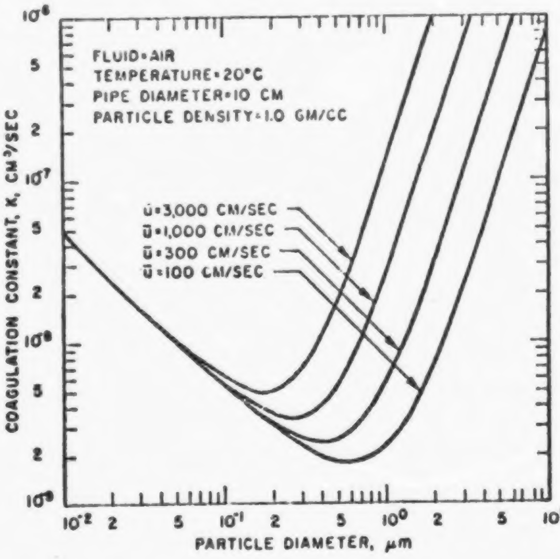

Figure A-8. Coagulation constants for various particle diameters and fluid velocities

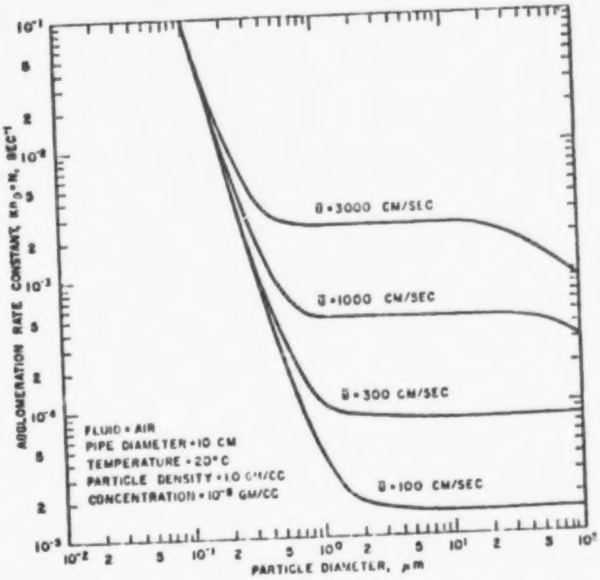

Figure A-9. Agglomeration rate constants for various particle diameters and fluid velocities

This is the equivalent to about 40 hp/1,000 $ft^3$. If this energy is expended over a period of 1 min, a 0.5 μ particle could be grown to about 2-3 μ. This is an extremely high energy consumption, and, therefore, turbulent agglomeration does not appear attractive for general use.

Agglomeration in Sonic Fields - Several different effects are responsible for the enhanced agglomeration rate due to sonic forces including (1) collection of the particles at the antinodes in the sonic standing wave (due to radiation pressure), (2) hydrodynamic forces between the particles, and (3) additional collisions due to the different vibrational amplitudes of different sized particles.

The relative importance of the three mechanisms cited above has not been determined. In fact, there is no assurance that other mechanisms are not important. It is, therefore, not possible to construct a theoretical model.

However, previous theoretical studies have developed equations which express the functional dependence of the three mechanisms.[5/] From a theoretical standpoint, all three mechanisms show a strong dependence on the radii of the particles, with the forces due to radiation pressure and hydrodynamics increasing with increasing particle size and the relative vibrational amplitudes decreasing with increasing particle size. There is also a strong frequency dependence in all the mechanisms and particle agglomeration becomes negligible at low frequencies. There is, therefore, an optimum frequency for acoustic agglomeration which varies with particle size.

Coagulation by a sonic field has as its principal advantage its applicability to any aerosol, including those comprised of submicron particles. The principal disadvantage of sonic coagulation is its moderately high energy requirements. A second major disadvantage is the low efficiency of acoustic coagulators and their inability to handle highly dispersed suspensions. Even with long residence times, sonic agglomerators which incorporate inertial separators for particle collection, cannot treat suspensions having particle loadings of < 0.5 to 1.0 grains/$ft^3$. It is, therefore, necessary to augment highly dispersed suspensions with a water mist or other particles to increase the particle loading and obtain satisfactory separation.

Water augmentation appears necessary to obtain the removal of a large fraction of the particulates. If a pound of water per 1,000 cfm is used, one would expect an increase in the power requirements of up to 1 hp/1,000 cfm, depending on the device used to introduce the water and the mean droplet size. The minimum energy requirements would then be 5.5 to 10 hp/1,000 cfm. Whether this is competitive with other devices capable of removing fine particles remains to be seen.

Agglomeration of Charged Particles - One method of increasing the rate of agglomeration of fine particulates is to add a bipolar charge, either with or without an externally imposed field. To a limited degree, this occurs in a standard electrostatic precipitator but not sufficiently to permit efficient collection of fine particulates. With proper conditions the large electrostatic forces between particulates can produce a large increase in the rate of agglomeration of submicron particulates.

Space-charge precipitation is a method of removing particulates from gas streams based on the migration of charged particles in their own space-charge fields. However, particulate gas systems are usually not sufficiently concentrated to provide adequate fields. It is, therefore, necessary to add a cloud of charged drops in order to produce fields which will remove the particles.

Basically, a space-charge precipitator consists of two parts: (1) a short section where both the particles and the added drops are charged by high voltage coronas; and (2) a section of grounded tubes or plates on which the particles and drops are collected. In the collecting section, the drops and particles migrate to the surfaces, where they coalesce and flow from the precipitator as a slurry.

Both theoretical and limited experimental studies on space-charge precipitation have been conducted at the University of California.19-21/ While the experiments may not accurately model a practical system, the calculations and experiments done to date indicate that space-charge precipitation may be a viable approach to the collection of particulates. Energy requirements for a space-charge precipitator are relatively uncertain. Calculations performed by investigators at the University of California indicate a total energy requirement of about 0.5 hp/1,000 cfm of gas. Based on a preliminary cost estimate, space-charge precipitation appears to be economically competitive with conventional electrostatic precipitation. Additional testing with a pilot-scale model on an actual industrial source will be needed to allow precise analysis of the potential of full-scale units.

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# APPENDIX B

## EXAMPLE OF PROCEDURE FOR DETERMINING CONTROL COSTS FOR COMPLIANCE WITH FINE PARTICLE EMISSION STANDARDS

### INTRODUCTION

The determination of the control costs required for compliance with various fine particle emission standards involves the following major steps:

1. Development of model plant for each industry category.

2. Determination of control-device performance required to meet a specific fine particle emission standard.

3. Determination of costs for model plant and industry for compliance with specific fine particle emission standard.

Individual steps in the procedure will be illustrated in the following sections using the coal-fired power plant category as an example.

### SPECIFICATION OF CHARACTERISTICS OF MODEL PLANT

1. Boiler type: pulverized coal fired.

2. Boiler capacity: 400 MW (existing boiler range from < 25 MW up to 1,000 MW or more).

3. Coal usage rate: assume boiler operates at 100% capacity at all times. Reference 1 states that a 400-MW plant would consume 150 tons/day.

4. Gas flow rate: Ref. 2 gives the following relation between boiler capacity and gas flow rate:

1 MW = 2,800 acfm[2]

Reference 3 indicates that a 400-MW plant would have a gas flow rate of 800,000 scfm. Assuming that the exit gas temperature is 300°F,2/ the gas flow rate given by Ref. 2 can be converted to scfm as follows:

$$\left(2{,}800\ \frac{\text{acfm}}{\text{MW}}\right)\ (400\ \text{MW})\ \left(\frac{520}{760}\right) = 765{,}000\ \text{scfm} \qquad (1)$$

Since the gas flow rate from Refs. 2 and 3 are in good agreement, the figure of 2,800 acfm/MW will be used in subsequent calculations.

5. Stack diameter: assume that the exit velocity of stack gas is 4,000 ft/min.

$$\text{Cross-sectional area of stack} = \frac{\text{Gas Flow Rate}}{\text{Exit Velocity}}$$

$$= \frac{\left[(2{,}800)\ \frac{\text{acfm}}{\text{MW}}\right]\left[400\ \text{MW}\right]}{4{,}000\ \text{ft/min}} \qquad (2)$$

$$= 280\ \text{ft}^2$$

$$\text{Stack diamter} = \left(\frac{4\ \text{Area}}{\pi}\right)^{1/2} \qquad (3)$$

$$= \left[\frac{(4)(280)}{\pi}\right]$$

$$= 18.9\ \text{ft} = 5.76\ \text{meters}$$

CONTROL DEVICE PERFORMANCE REQUIRED TO MEET PLUME OPACITY REGULATION

Equation (4) was used to calculate the allowable outlet grain loading for a specific plume opacity.

$$W = -K\ \rho/L\ \text{In}\ \frac{I}{I_o} \qquad (4)$$

The efficiency of the control device was then determined from Eq. (5).

$$\text{Efficiency} = \frac{\text{Inlet Grain Loading - Outlet Grain Loading}}{\text{Inlet Grain Loading}} \qquad (5)$$

The inlet grain loading to the control device for the model plant was calculated from the relation:

$$\text{Inlet Grain Loading} = \frac{\text{(Emission Factor) (Coal Usage Rate)}}{\text{Gas Flow Rate}} \qquad (6)$$

$$= \frac{\left(190\ \frac{\text{lb}}{\text{ton of coal}}\right)\ \left(150\ \frac{\text{ton coal}}{\text{hr}}\right)\ \left(7{,}000\ \frac{\text{grain}}{\text{lb}}\right)}{60\ \frac{\text{min}}{\text{hr}} \qquad 1.12 \times 10^6\ \frac{\text{acf}}{\text{min}}}$$

$$= \left(2.97\ \frac{\text{grain}}{\text{acf}}\right)\ \left(\frac{460 + 300}{460 + 60}\right)$$

$$= 4.34\ \text{grains/scf}$$

The allowable grain loading at the outlet of the control device for plume opacities of 5% and 10% and the corresponding required control device efficiency are given in Table B-1.

Table B-1. SUMMARY OF CONTROL EQUIPMENT PERFORMANCE REQUIRED TO MEET PLUME OPACITY REGULATIONS
(Coal-Fired Power Plant)

| Plume Opacity Permitted | Outlet Grain Loading (grain/scf) | Overall Mass Efficiency of Control Device |
|---|---|---|
| 10% | 0.0149 | 99.66 |
| 5% | 0.00728 | 99.83 |

The main type of control device currently installed on coal-fired power plants to control particulate emissions is the electrostatic precipitator. The cost of an electrostatic precipitator for the model plant was determined from Figures 17 and/or 18, Chapter 6, and the cost for the total industry was determined using the following equation:

$$\text{Total Cost} = \left(\frac{\text{Total Industry Production Capacity}}{\text{Model Plant Production Capacity}}\right) \left(\text{Cost for Model Plant}\right) \quad (7)$$

Table B-2 summarizes the calculation of the annualized costs required to meet a 10% or 5% plume opacity standard.

## CONTROL SYSTEM CORRESPONDING TO BEST INSTALLED CONTROL DEVICE

Electrostatic precipitators are the most efficient particulate control devices currently being installed on coal-fired power plants. Reference 2 indicates that the average design efficiency of electrostatic precipitators installed on power plants in the 1970-1971 period was 99% (overall mass efficiency). The cost of this control device was determined from Figures 17 and/or 18, Chapter 6.

## COMPARISON OF CONTROL EQUIPMENT COSTS

Table B-3 presents a comparison of the control costs required for compliance with the two fine particle emission standards.

Table B-2. ANNUALIZED COSTS FOR POWER PLANTS TO MEET 10% AND 5% PLUME OPACITY STANDARD

| Opacity Standard | Control Device Required | Annualized Cost | |
|---|---|---|---|
| | | Model Plant | All Plants |
| 10% Opacity | 99.66% Electrostatic precipitator | (a) \$0.22/cfm/year<br>(b) (\$0.22/cfm/year) (1.12 x $10^6$ cfm) = \$2.5 x $10^5$/year | $\left(\frac{150,000 \text{ MW}}{400 \text{ MW}}\right)$ (\$2.5 x $10^5$/year) = \$94 x $10^6$/year |
| 5% Opacity | 99.83% Electrostatic precipitator | (a) \$0.27/cfm/year<br>(b) (\$0.27/cfm/year) (1.12 x $10^6$ cfm) = \$3.0 x $10^5$/year | $\left(\frac{150,000 \text{ MW}}{400 \text{ MW}}\right)$ (\$3.0 x $10^5$/year) = \$112 x $10^6$/year |

Table B-3. ANNUALIZED COSTS FOR POWER PLANTS TO MEET 10% AND 5% PLUME OPACITY AND BEST INSTALLED CONTROL STANDARD

| Emission Regulation | Control System | Annualized Cost ($/Year) Model Plant | Annualized Cost ($/Year) All Plants | Incremental Annualized Cost ($/Year) Model Plant | Incremental Annualized Cost ($/Year) All Plants |
|---|---|---|---|---|---|
| Best installed control device | 99% Electrostatic precipitator | 190,000 | $71 \times 10^6$ | -- | -- |
| 10% Opacity | 99.66% Electrostatic precipitator | 250,000 | $94 \times 10^6$ | 60,000 | $23 \times 10^6$ |
| 5% Opacity | 99.83% Electrostatic precipitator | 300,000 | $112 \times 10^6$ | 110,000 | $41 \times 10^6$ |

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## APPENDIX C

## PLUME OPACITY

The opacity of a plume is defined as one minus the transmittance of the plume, i.e.,

$$\text{Plume Opacity} = 1 - \text{Transmittance} \qquad (1)$$

Plume transmittance can be calculated from Eq. (2):1,2/

$$T = \frac{I}{I_o} = \exp\left[-\pi L \int_{r_1}^{r_2} Q_E(\alpha,m) r^2 n(r) dr\right] \qquad (2)$$

where,

$\alpha$ = Size parameter, $2\pi r/\lambda$,

r = Particle radius,

$\lambda$ = Wavelength of light,

m = Refractive index of the particles relative to air,

n(r) = Size frequency distribution, number of particles of radius r per volume per $\Delta r$,

$Q_E(\alpha,m)$ = Particle light extinction efficiency factor, the total light flux scattered and absorbed by a particle divided by the light flux incident on the particle,

L = Plume width,

$I$ = Intensity of transmitted light, and

$I_o$ = Intensity of incident light.

The light extinction efficiency factor $Q_E$ for spheres, ellipsoids and cylinders can be computed using the Mie equations.[4] For pure scatterers with typical refractive indices, $Q_E$ can vary from near zero for very small particles, to about four when the particle diameter is near the wavelength of light, and approaches a theoretical limit of two for very large particles. For spherical particles,

$$n(r) = \frac{3\ W\ g(r)}{4\pi r^3 \rho} \tag{3}$$

where,

$W$ = Mass concentration of particles in exhaust stream,

$\rho$ = Particle density, and

$g(r)$ = Mass distribution function.

Substitution of Eq. (3) into (2) yields:

$$T = \exp\left[-3/4\ \frac{WL}{\rho} \int_{r_1}^{r_2} \frac{Q_E}{r}\, g(r)dr\right] \tag{4}$$

By suitable rearrangements of the preceding equations, Pilat and Ensor[2] have developed a simplified equation to calculate the expected mass concentration for various values of plume transmittance (or opacity), average particle density, and plume diameter.

$$W = -K\ \rho/L\ \ln\ (I/I_o) \tag{5}$$

where,

$$K = \frac{\text{Specific particulate volume}}{\text{Extinction coefficient}}$$

The parameter K is dimensionally similar to the volume surface characteristic size described by Herdan (1960).[3] K is primarily a function of the particle size distribution, refractive index, and to a lesser degree, the wavelength of light.

Equation (4) can be used to obtain an understanding of the dependence of opacity on various parameters, and thereby, some important implications regarding the use of opacity as an indicator of fine particulate emission. The effect of mass concentration, path length, and particle density on the transmittance can be evaluated directly from Eq. (4).

If $\beta$ is defined as $WL/\rho$, and $I'$ is $3/4 \int (\frac{Q_E}{r})\, g(r)dr$, then Eq. (4) becomes:

$$T = \exp(-\beta I') \tag{6}$$

For a constant $I'$, a change in $\beta$ from $\beta_1$ to $\beta_2$ results in a change in transmittance given by:

$$T_2 = T_1^{\beta 2/\beta 1} \tag{7}$$

Thus, the percentage change in transmittance caused by a change in W, L, or $\rho$ depends on the initial transmittance level. For example, a doubling of W or of L or a halving of $\rho$ will result in an 80% reduction of transmittance of $T_1 = 0.2$ or a 20% reduction if $T_1 = 0.8$.[1]

The optical properties of particles are described by the refractive index, which is a complex number, $m = n_1 - in_2$. The real part, $n_1$, describes the light-scattering properties and the imaginary part, $n_2$, describes the light absorption of the particulate material. The refractive index has a strong influence on the evaluation of $Q_E$ and, hence, on the transmittance.

Figure C-1 shows percent opacity plotted against the mass median radius for a hypothetical case. Four curves are plotted, each for a different value of m from 1.33 to 3.0 with $n_2$ assumed equal to zero. Thus, the effect of the real part of the refractive index on opacity is illustrated. The lower value of $m = 1.33$ represents water droplets in air. The $m = 1.5$ curve approximates the inorganic components of fly ash. The higher values of m are typical of iron oxide, for example.[1]

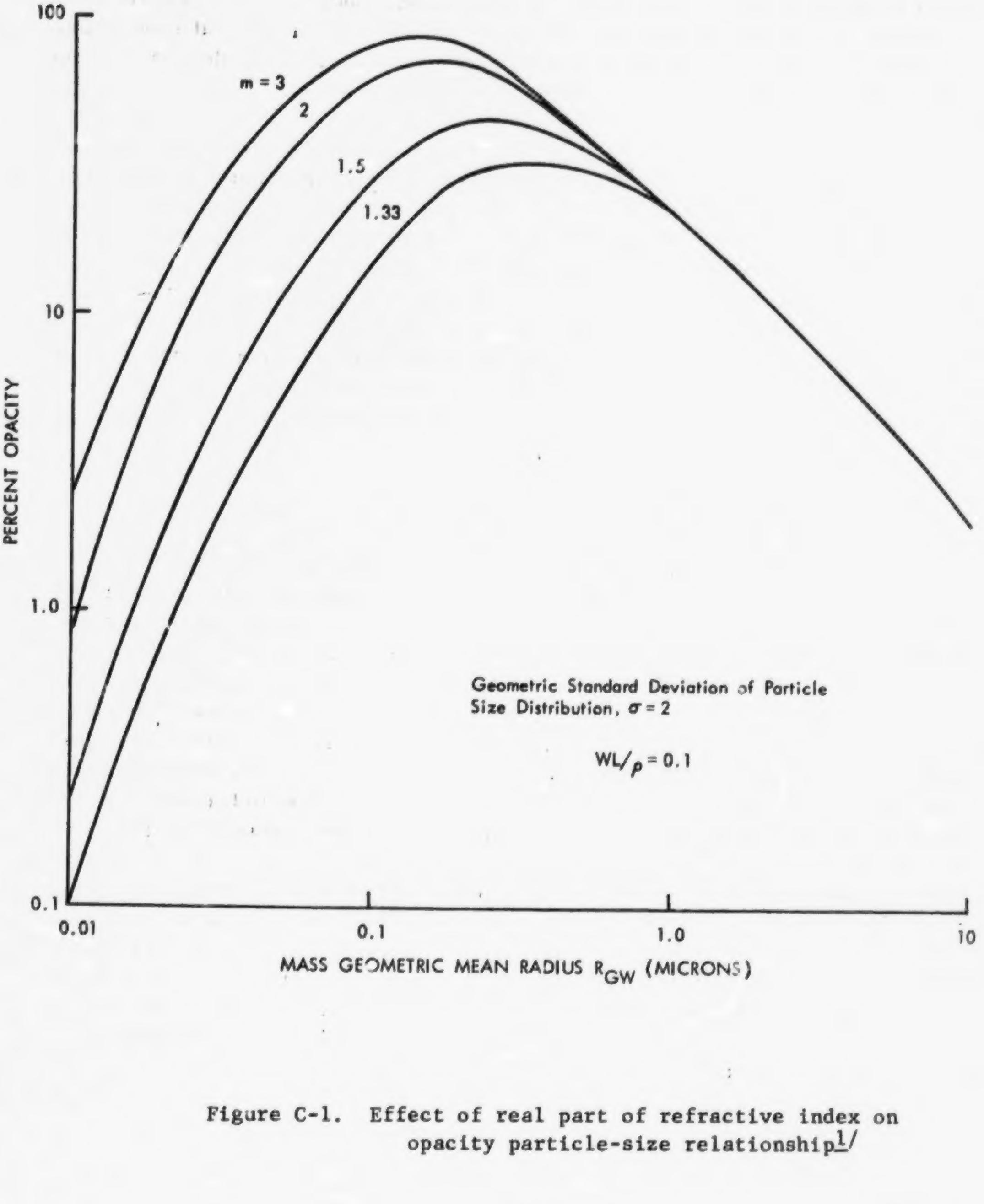

Figure C-1. Effect of real part of refractive index on opacity particle-size relationship1/

It is important to note that all of the curves show a maximum opacity in the 0.1-0.3 μm range, the opacities falling off rapidly on either side of the maximum. About 1 μm the curves merge and opacity is independent of the refractive indices. For finer particles, the higher values of refractive index result in higher opacities. A plume composed of iron oxide particles will, therefore, transmit less light than a fly ash plume of identical characteristics. For the case where the plumes have identical characteristics, different levels of plume opacity would, in fact, represent the same level of fine particulate emissions to the atmosphere.

Figure C-2 illustrates the effect of the imaginary part of the refractive index, i.e., light absorption, on opacity. The four curves plotted represent refractive indices all with $n_1 = 1.5$ but with $n_2$ varying from 0 to 0.9. The effect is significant. For mass median radius less than 0.5 μm, light absorption by fine particles plays a dominant role in determining opacity. In fact, for the higher values of $n_2$, the calculated opacities become virtually independent of particle size. This has important implications in the use of opacity as an emission indicator. High opacities could be measured in a plume composed of very fine absorbing particles whereas an identical plume of nonabsorbing particles might go unnoticed.[1]

Particle size distribution also exerts a strong influence on plume opacity because of the fact that particles in different size ranges contribute unequally to the overall opacity. For nonabsorbing particles, a given mass of particles less than 0.1 μm contributes less and less to opacity as the particle size decreases. Above 1 μm the same is true as size increases. As a result, particulates which are monodisperse or nearly so, should be expected to yield opacities which show a greater dependence on particle size than more polydisperse distributions.[1]

Figures C-3 and C-4 show the composite effects of some of the main parameters on the plume opacity as expressed in terms of the parameter K, developed by Pilat and Ensor.[2] Figure C-3 shows the functional dependence of K on size distribution parameters for a black aerosol, while Figure C-4 depicts the same relationships for a white aerosol.[2]

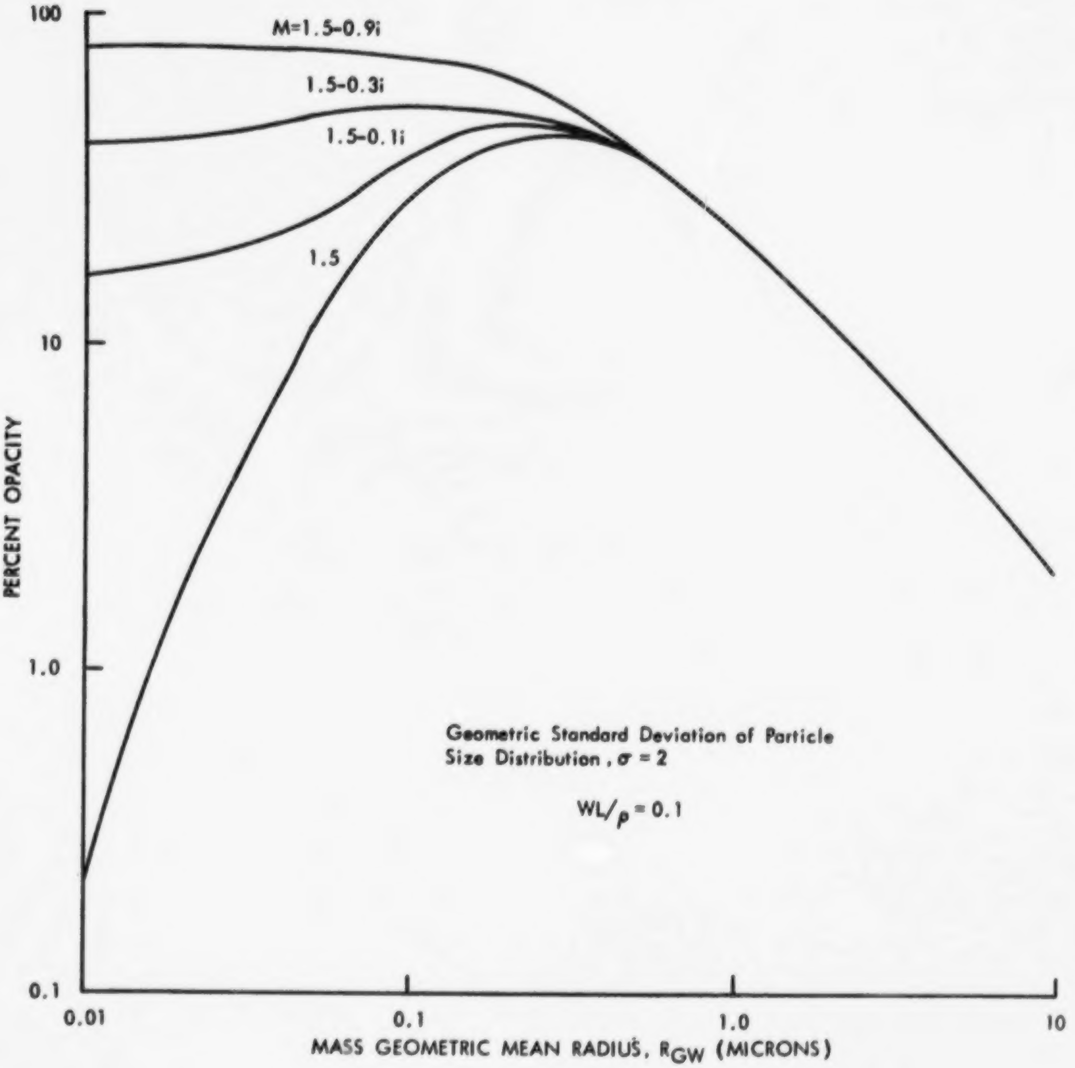

Figure C-2. Effect of imaginary part of refractive index on opacity particle-size relationship[1/]

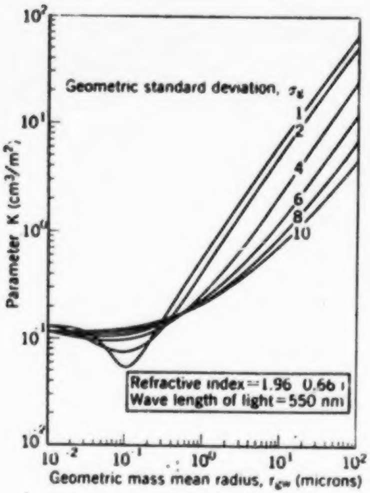

Figure C-3. Parameter K as a function of log-normal size distribution parameters for black aerosol[4]

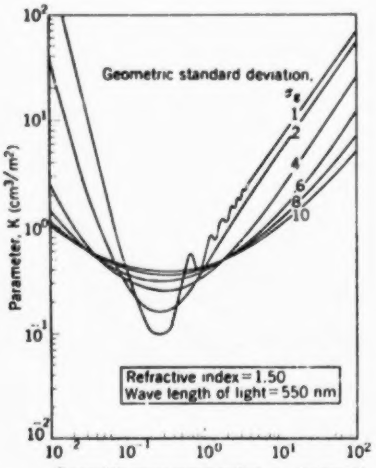

Figure C-4. Parameter K as a function of the log-normal size distribution parameters for a white aerosol[4]

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